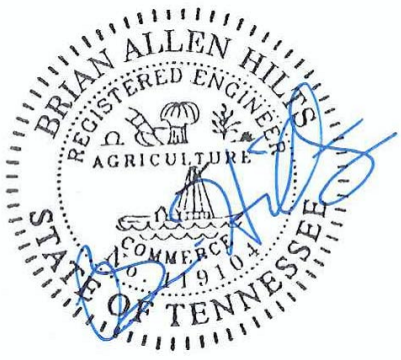
FINAL

REPORT

Maxson Disinfection Alternative Evaluation Report



City of Memphis, TN

February 2017

CDM Smith

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Section ES
Executive Summary

This report describes results of pilot and bench-scale testing conducted at the T.E. Maxson wastewater treatment plant (Maxson WWTP) in 2013 and 2015 as part of the City of Memphis Disinfection Study Project. Pilot scale testing in 2013 was conducted for sodium hypochlorite, peracetic acid (PAA), and ultraviolet (UV) disinfection to compare and determine disinfection efficacy. During the 2013 testing a portion of the plant's treatment processes were being bypassed, potentially impacting the effluent water quality, and a significant industrial user came off line after the 2013 pilot testing. Supplemental pilot and bench-scale testing performed in 2015 was conducted for PAA, UV, and UV/PAA in combination to determine if there was an improvement in effluent water quality, and thus disinfectant performance, after these changes. The City of Memphis (City) has contracted with CDM Smith to evaluate potential process improvements that could improve effluent quality and process control. Using information from the process analysis for the Maxson WWTP and the design doses developed based on pilot and bench testing, CDM Smith prepared planning level capital, operations and maintenance cost estimates for each disinfection alternative.

The original pilot scale testing began in March 2013. Pipe reactors were constructed on location in which plant effluent was treated with either sodium hypochlorite or peracetic acid. UV testing was also performed in a trailer mounted UV disinfection pilot from Trojan Technologies. Control samples were analyzed for color, UV transmittance (UVT) total suspended solids (TSS) *Escherichia coli (E. coli)*, and disinfection by-products (DBPs). Treated samples were analyzed for *E. coli* and disinfection by-products. Testing results with respect to recommended design doses are presented in this report, which is divided into five major sections. Testing objectives, background and permit requirements are described in Section 1, procedures are outlined in Section 2, results and recommendations for design doses are presented in Section 3, and conceptual cost estimates are summarized in Section 4.

The results of the pilot scale testing showed that sodium hypochlorite and PAA could be effective for achieving bacterial inactivation to meet permit compliance for *E. coli*, which includes a monthly geometric mean of 126 colony forming units (cfu)/100 mL, with a daily single grab maximum of 487 cfu/100 mL under current plant operating conditions. In addition to *E. coli* inactivation, DBP formation potential was evaluated for sodium hypochlorite and peracetic acid. Dioxin congeners were detected in the undisinfected effluent and sometimes persisted into the disinfected water. Disinfection did not increase the occurrence or concentration of dioxin congeners. Sodium hypochlorite was also found to form low concentrations of trihalomethanes (THMs) at the doses that were effective for disinfection. NDMA was not detected in any sample.

Prior to proceeding with the disinfection design phase, the City and CDM Smith agreed that supplemental pilot and bench testing was necessary to determine the impacts the two changes at the Maxson WWTP had on disinfection efficacy. The supplemental pilot-scale testing began in early May 2015 and concluded in early June 2015, while the UV/PAA bench-scale testing was conducted over a week in late September 2015. The supplemental testing had the following objectives:

- Refine the design criteria for PAA disinfection to meet disinfection limits

  - Determine the kinetic model parameters to predict PAA disinfection efficacy across a range of doses and contact times
  - Determine the design dose for average conditions to support calculation of associated operating costs
- Confirm the UV disinfection design dose to support estimates of capital and operating costs
- Quantify and compare disinfection kinetics among several UV and PAA combinations including:
  - PAA alone, UV alone, UV followed by PAA, PAA followed by UV, simultaneous disinfection with UV and PAA.
- Propose a mechanistic model to describe the efficacy of the combined disinfectant

The supplemental PAA pilot testing allowed for the development of a kinetic model to predict PAA disinfection efficacy across a range of doses and contact times. During the analysis of the dataset it was determined that a double exponential decay model provided the best correlation with the dataset, and it was shown to have a reduced spread between the data and the model, when compared to Hom's Model or the standard CT model. Therefore, the double exponential decay model was utilized to determine the necessary CT values at the minimum, average and maximum design conditions. **Table ES-1** summarizes the design criteria for the PAA system.

Table ES-1: Required PAA CTs and Design Points

Flow Conditions	Flow (MGD)	Required Log Inactivation	CT*
Permitted Average	90	µ.92	87.1
Peak Hour	170	µ.82	74.1
Daily Minimum	50	2.81	22.4

*CT results include a 1.µx safety factor for scaling up to full scale

The results from the recent collimated beam analysis were compared against the historical collimated beam data. It was found that there is no significant difference between the two datasets. Therefore, the water quality at the time of the 2013 sampling and the 2015 sampling yielded nearly identical collimated beam results. The supplemental pilot and bench testing data showed that a design UVT of 20% would be more reasonable than the UVT value of 35%, which was utilized previously.

The data from the bench testing of a combined UV/PAA disinfectant indicated that the most consistent and positive results occurred with UV followed by PAA. Although the results are promising, further research is required to accurately describe the effect of combined disinfection, and the economic analysis that was performed based on the results did not indicate significant economic savings through application of a combined disinfection system.

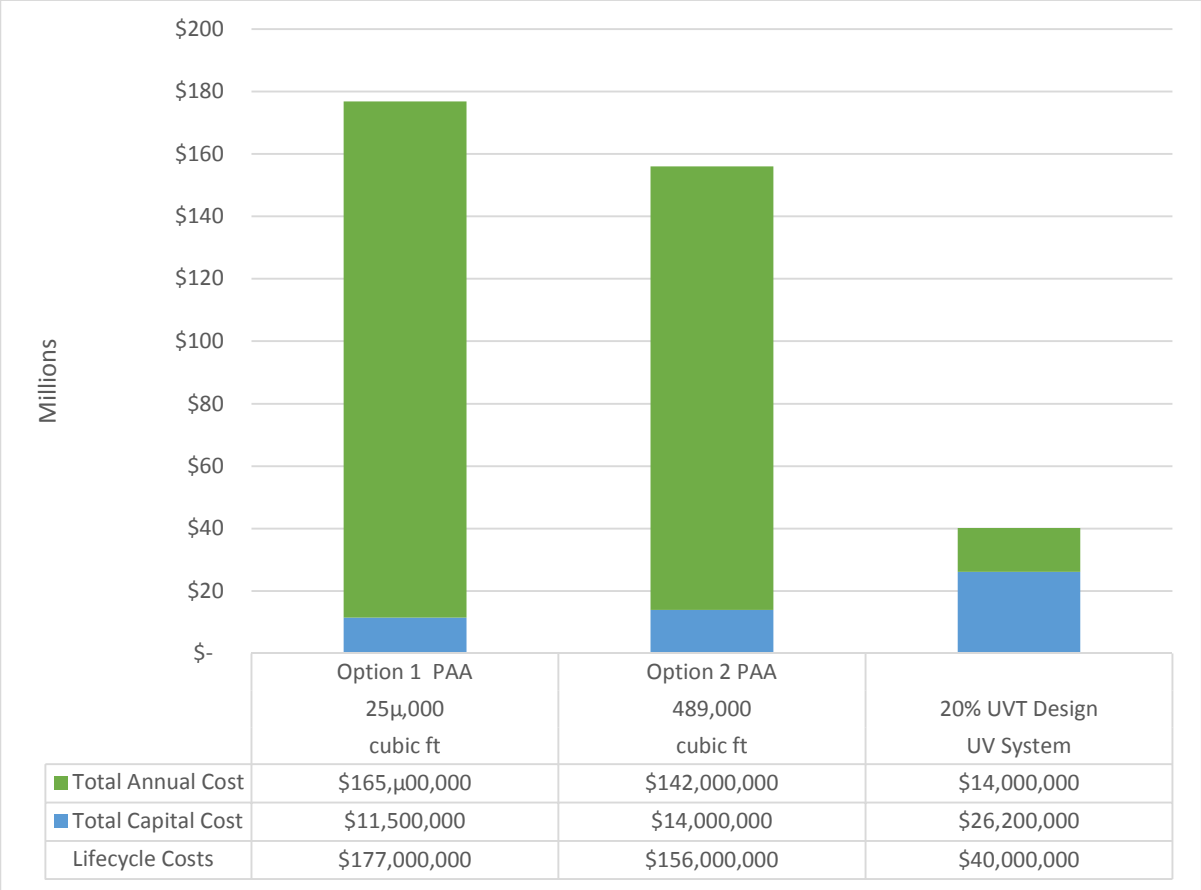
Further discussions regarding the use of chlorine disinfection were had between CDM Smith and the City. Use of chlorine disinfection has lower lifecycle costs and similar capital costs to PAA disinfection, however the use of a chlorination disinfection system has additional permitting requirements that include additional testing under Section 3.6.1 of the permit, as follows, making the technology more challenging to implement:

"3.6.1 Additional Permittee Submittals (If Chlorination Disinfection System Selected)

Permittee must provide the division with the types/amounts of specific chlorinated byproducts species to be in the Outfall 001 treated effluent and how newly generated byproducts are related to TRC according to the compliance schedule…"

As a result of the additional testing required in the permit, it was determined that chlorine disinfection would no longer be considered.

Based upon the supplemental testing performed in 2015, the conceptual costs for UV and PAA were revised. Comparative 20 year lifecycle costs for three alternative disinfection systems are illustrated in **Figure ES-1**. The first alternative is a PAA system with a contact tank providing 31 minutes of contact time at average flow, the second is a PAA system providing 31 minutes of contact team at peak flow, and the third is a UV system designed to treat effluent with a 20% UVT.



	Option 1 PAA 25µ,000 cubic ft	Option 2 PAA 489,000 cubic ft	20% UVT Design UV System
Total Annual Cost	$165,µ00,000	$142,000,000	$14,000,000
Total Capital Cost	$11,500,000	$14,000,000	$26,200,000
Lifecycle Costs	$177,000,000	$156,000,000	$40,000,000

Figure ES-1 20 Year Lifecycle Analysis of Three Disinfection Options

Providing more contact time at average flow for the PAA system eliminated the need for quenching with sodium bisulfite, although the capital costs for a small sodium bisulfite was included for emergency use. Although the lifecycle costs of the UV alternative is lower than that of the two PAA alternatives, the City of Memphis and CDM Smith discussed the impacts caused by the variability of the low UV transmittance seen in the Maxson WWTP effluent. The variability likely stems from the change in processes and raw materials utilized by industrial users within the City's collection system. In addition, the capital cost required to increase the UVT of the effluent via another treatment process, such as ozone, to make UV disinfection a viable option, is cost prohibitive for the City. Based upon

these discussions it was decided to eliminate UV from the list of disinfection alternatives. Therefore PAA disinfection is the recommended disinfection alternative to be utilized at the Maxson WWTP. Further analysis was performed to find the optimal combination of contact tank size and PAA dose to reduce the lifecycle costs. Results from the detailed cost analysis and the supplemental pilot data indicate that the most cost effective contact tank size to reduce overall lifecycle cost is 489, 235 cubic ft. As a result, the most cost effective disinfection alternative is PAA - Option 2.

If the City opts to implement PAA disinfection and the associated secondary treatment upgrades to address chemical oxidant demands in the effluent, there are significant ancillary benefits to this decision. While PAA disinfection has the highest lifecycle cost, the low capital cost of the PAA disinfection system combined with the avoidance of additional permitting requirements as described above, has resulted in PAA disinfection being the selected disinfection alternative for the Maxson WWTP. Additionally, proceeding in this direction may enable the City to address other major concerns regarding odor control and future capacity issues at the Maxson WWTP.

Section 1
Introduction

1.1 Facility Background

Raw wastewater influent to the Maxson WWTP flows through coarse bar screens and aerated grit tanks for removal of large organic and inorganic constituents in the raw wastewater. From the grit tanks, flow passes through new fine bar screens before it passes to the primary clarifiers. Primary clarifier effluent is pumped to the activated biological filter towers which provide gross removal of wastewater organic constituents, followed by biological treatment in aeration tanks and secondary clarifiers before discharge into the Mississippi River. A process flow diagram for the Maxson WWTP is provided in **Figure 1-1**.

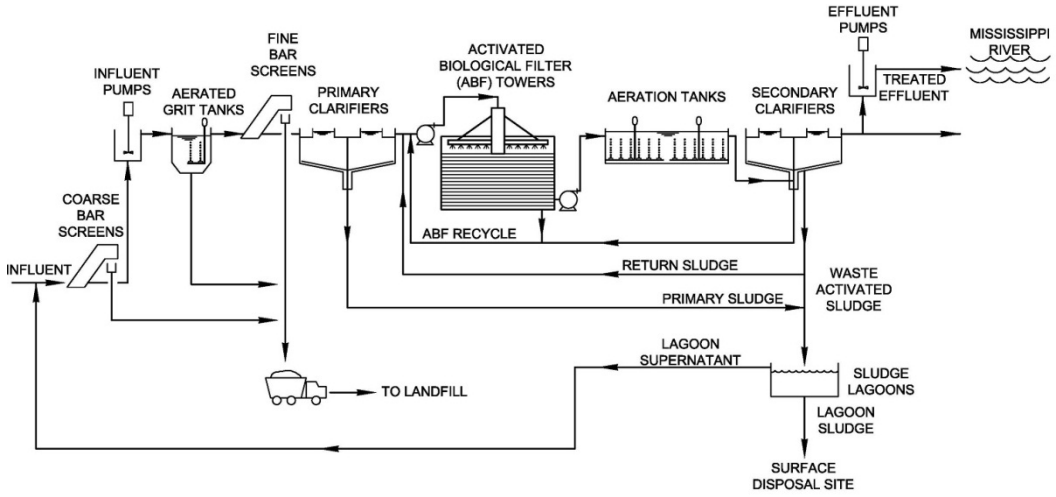


Figure 1-1 Process flow diagram of Maxson WWTP

A summary of historical effluent wastewater characteristics that are important in selection of a disinfection technology is provided in **Table 1-1**. The NPDES permit limits are included in the table for reference.

1.2 NPDES Permit Requirements

The current NPDES permit, number TN0020729, issued by Tennessee Department of Environment and Conservation (TDEC) authorizes the Maxson WWTP to discharge treated effluent from Outfall 001 to the Mississippi River at Mile 725.0, pursuant to the permit limits and monitoring requirements specified in the permit. The facility, as noted in the permit, has a treatment design capacity of 90 million gallons per day (MGD) with a peak hour hydraulic capacity of 170 MGD. The effluent limits for parameters relevant to the evaluation of disinfection processes are summarized in **Table 1-2**.

Table 1-1 Effluent water quality characteristics at the Maxson WWTP

Parameter	Daily Performance Data			NPDES Limit		
	Minimum observed	Average or mean[1]	Maximum observed	Daily (minimum and) maximum	Weekly maximum	Monthly maximum
Daily Flow (MGD)[2]	18	78	170	90[12]	-	-
BOD_5 (mg/L)[µ]	4	29	177	84	6µ	42
TSS (mg/L)[4]	4	µ0	201	96	72	48
pH[4]	6.2	7.µ	8.5	(6.0) - 9.0	-	-
E. coli (cfu/100mL)[5]	1.µ x 10^4	7.4 x 10^5 (5.2 x 10^5 as geomean)	5.7 x 10^6 (2.0 x 10^6 is 99-percentile)	487	-	126 as a geomean
Apparent Color (PtCo units)[6]	28	401	1152	-	-	-
True Color (PtCo units)[7]	8	109	496	-	-	-
Apparent UVT (%)[8]	2 (1µ)[9]	25	50	-	-	-
Filtered UVT (%)[10]	11 (µ1)[11]	41	58	-	-	-

[1]Arithmetic means were reported for all values except *E. coli* which is also reported as a geometric mean.
[2]Average daily influent flow values; period of record = 1/1/08-5/µ1/201µ.
[µ]Daily values taken from composite effluent samples; period of record = 1/1/08-5/µ1/201µ.
[4]Daily values taken from period of record = 1/1/08-5/µ1/201µ.
[5]Daily values taken from effluent grab samples; period of record = 9/14/2010-7/11/201µ.
[6]Daily values taken from composite effluent samples; period of record = 6/28/2011-12/2/2012.
[7]Daily values taken from composite effluent samples; period of record = 6/28/2011-12/2/2012.
[8]Daily values taken from composite effluent samples; period of record = 8/11/2011-12/27/2011.
[9]In parentheses: lowest 10th percentile of apparent UVT data on record.
[10]Daily values taken from composite effluent samples; period of record = 8/11/2011-12/27/2011.
[11]In parentheses: lowest 10th percentile of filtered UVT data on record.
[12]The NPDES Permit value for flow is shown as a "permitted average capacity" and not as a limit.

Table 1-2 Select NPDES permit effluent limits for the Maxson WWTP

Effluent Characteristics	Monthly	Weekly	Daily	
	Maximum (Average)	Maximum (Average)	Maximum	Minimum
BOD_5 (mg/L)	42	6µ	84	-
BOD_5 (lb/day)[1]	µ1,525	47,288	-	-
TSS (mg/L)	48	72	96	-
TSS (lb/day)[1]	µ6,029	54,04µ	-	-
E. coli (cfu/100 mL)[2,µ]	126	-	487	-
Total Residual Chlorine (TRC) or Total Residual Oxidant (TRO) (mg/L)[1]	-	-	2.0	-
pH (standard units)	-	-	9.0	6.0
Total Dioxin (µg/L)	0.000001	-	0.000001	-

[1]These permit limits are subject to the pending NPDES permit appeal.
[2]The concentration of the *E. coli* group after disinfection shall not exceed 126 cfu per 100 mL as the geometric mean calculated on the actual number of samples for *E. coli* within the required reporting period. The permittee may collect more samples than specified as the monitoring frequency but, not at intervals of less than 12 hours. For the purpose of determining the geometric mean, individual samples having an *E. coli* group concentration of less than one (1) cfu per 100 mL shall be considered as having a concentration of one (1) cfu per 100 mL.
[µ]The compliance schedule pertaining to *E. coli* permit limits is subject to the pending NPDES permit appeal.

1.µ Pilot Study Objectives

In order to meet the new permit requirements, a new disinfection system will be required at the existing facility. While a desktop evaluation can provide planning level costs, the complex nature of the effluent, considering the significant industrial contributions to the WWTP influent, necessitates site-specific data to identify engineering design criteria for the facility as well as the operational parameters that would allow the Maxson WWTP to meet both bacterial standards and limits for disinfection by-products (DBPs). In support of developing this information, a pilot study was conducted to evaluate three disinfection technologies that were previously identified as feasible options to meet NPDES permit requirements. Specific goals of the pilot project were to:

- Determine the required disinfection dose, residual, and contact time to achieve compliance with *Escherichia coli (E. coli)* permit limits using sodium hypochlorite, UV, and PAA.
- Identify how total suspended solids (TSS), ultraviolet transmission at 254nm (UVT) and color impact disinfection performance.
- Characterize the potential formation of regulated DBPs for chlorination using sodium hypochlorite.
- Evaluate process control options for disinfection using total residual chlorine or peracetic acid residual.
- Develop comparative capital and operating cost estimates for each technology to support recommendations for selection and implementation of the disinfection method that most cost-effectively meets the new permit requirements.

1.4 Pilot Study Evaluation Criteria

To meet the objectives of the pilot study, specific criteria for determining whether a disinfection alternative could meet the permit requirements were developed. The following sections include a description of the development of criteria for evaluation of bacteria inactivation and DBP formation.

1.4.1 Bacteria Inactivation

Considering the new permit limits that have been added for *Escherichia coli* (*E. coli*), it is important to evaluate the target removal that is required to provide discharge compliance. For the Maxson WWTP, treated effluent (which would be influent to the proposed new disinfection system) had an average, historical *E. coli* concentration of 7.4 x 10^5 cfu/100mL for the period of 9/14/2010 through 7/11/13. The maximum recorded *E. coli* concentration during this same period was 5.7 x 10^6 cfu/100mL. The permitted effluent *E. coli* limit includes a monthly geometric mean of 126 cfu/100mL and a daily maximum of 487 cfu/100mL, therefore the inactivation rates required to consistently meet the NPDES permit requirements were calculated as follows:

Average Monthly Inactivation Rate Required[1]*:* $\log(7.4 \times 10^5) - \log(1.26 \times 10^2) = \mu.8$

Maximum Daily Inactivation Rate Required[2]*:* $\log(5.7 \times 10^6) - \log(4.87 \times 10^2) = 4.1$

[1]Based on average of all observed data which slightly more conservative than using the geometric mean.

[2]Based on maximum of historic observed values.

It is of interest to note that because the maximum effluent *E. coli* concentration is not substantially greater than the average value (i.e., there is not a high level of variability in the effluent bacterial

concentrations), the maximum inactivation rate is nearly the same as what is required for the average inactivation rate. Thus, considering that plant operations staff would not likely run the process on the edge of the compliance limit, it is recommended to use one half of the monthly geometric mean value (63 cfu/100 mL) in new permit to establish the baseline condition for operations. Thus, target operating limits that have been added for *E. coli* as follows in order to develop average operational doses for chlorine, PAA and UV disinfection:

Average Operating Inactivation Rate Required[1]*:* $\log(7.4 \times 10^5) - \log(6.\mu \times 10^1) = 4.1$

[1]Based on average of all observed data which slightly more conservative than using the geometric mean.

1.4.2 Disinfection Byproduct Formation

In addition to discharge limits, TDEC may require additional investigations to characterize and control chlorinated DBPs, if chlorination is chosen as the preferred disinfection method. In the permit for the Maxson WWTP, Section 3.6.1., ***Additional Permittee Submittals (If Chlorination Disinfection System Selected)***, indicates that the Permittee must provide the division with the types/amounts of specific chlorinated byproducts species to be in the Outfall 001 treated effluent and how newly generated byproducts are related to TRC according to the compliance schedule provided in the permit.

Further, TDEC water quality criteria for the receiving reach of the Mississippi River include standards for DBPs. The designated uses of the receiving reach of the Mississippi River in Tennessee are: Industrial Water Supply, Fish and Aquatic Life, Recreation, Livestock Watering and Wildlife, Irrigation and Navigation. The general water quality criteria for these designated uses are provided in the Rules of the TDEC Tennessee Water Quality Control Board Division of Water Pollution Control, Tennessee Code Annotated (TCA) Chapter 1200-04-03.

The Fish and Aquatic Life and Recreation use in-stream water quality criteria contain parameters that are relevant to chlorine disinfection as summarized in **Tables 1-3** and **1-4**. These parameters provide the basis of the analytical testing of DBP formation. Criteria for Industrial Water Supply, Livestock Watering and Wildlife, Irrigation, and Navigation designated uses are narrative and do not contain additional specific chemical constituents of concern to disinfection.

Table 1-µ Analytical parameters based on TDEC Numeric Criteria for Fish and Aquatic Life

Compound	Criterion Maximum Concentration (CMC) (µg/L)	Criterion Continuous Concentration (CCC) (µg/L)
Total Residual Chlorine (TRC)	19	11

Table 1-4 Analytical parameters based on TDEC Numeric Criteria for Recreation

Compound		Organisms Only Criteria[1] (µg/L)
Dioxin[2]		0.000001
Trihalomethanes (THMs)	Bromoform	1400
	Chlorodibromomethane	1µ0
	Chloroform	4700
	Dichlorobromomethane	170
N-Nitrosodimethylamine (NDMA)		µµ

[1] "Organisms Only" Criteria for Recreation refers to the protection of public health due to the consumption of organisms. Different criteria exist where the water impacts both the consumption of water and organisms, i.e. where the water is designated for both recreation and domestic water supply.

[2] Total dioxin is the sum of all dioxin and dibenzofuran isomers after multiplication by Toxic Equivalent Factors (TEFs).

1.4.µ Summary of Evaluation Criteria for Pilot Testing

Considering the NPDES permit and TDEC water quality requirements, a list of parameters were developed to aid in evaluating disinfection technologies (**Table 1-5**).

Table 1-5 Summary of criteria for evaluation of disinfection technologies

Parameter		Objective	Source of Requirement
E. coli (post-disinfection)		487 cfu/100 mL daily maximum; 126 cfu/100 mL monthly maximum	NPDES permit
E. coli Inactivation		4.1 log	Based on the NPDES permit limits and data on record regarding current effluent *E. coli* concentrations (see Section 2)
TRC or TRO		2.0 mg/L	NPDES permit; Also relevant to fish and aquatic life criteria
Total Dioxin		0.000001 µg/L	NPDES permit; TDEC Recreational use criteria for organisms
THMs	Bromoform	1400 µg/L	Recreation use criteria for organisms
	Chlorodibromomethane	1µ0 µg/L	Recreation use criteria for organisms
	Chloroform	4700 µg/L	Recreation use criteria for organisms
	Dichlorobromomethane	170 µg/L	Recreation use criteria for organisms
NDMA		µµ µg/L	Recreation use criteria for organisms

Section 2
Pilot Testing Procedure

Pilot tests were conducted at the Maxson WWTP between 3/5/2013 and 4/5/2013. Two chemical disinfection pilot reactors were constructed onsite using Schedule 40 PVC pipe and included flow control, flow metering, chemical injection points and in-line mixing. Sample ports were located along the length of the reactors that allowed sample collection at various time points. The flow rate through the PAA system was 100 gallons per minute (gpm), and flow rate through the hypochlorite system was 25 gpm. A photograph of the chemical disinfection reactors are shown in **Figure 2-1**. The reactors were fed from a common header (**Figure 2-2**) with plant effluent pumped from the Parshall flume (**Figure 2-3**). Chemical disinfectants were pumped via diaphragm pumps into static mixers at the head of the pipe reactors (**Figure 2-4**). Water samples were collected from sample taps (**Figure 2-5**) located along the reactor length and that correspond to specific contact times.

Figure 2-1 Pilot Reactor System

Figure 2-2 Common Feed Header System

Figure 2-µ Parshall flume and feed pumps

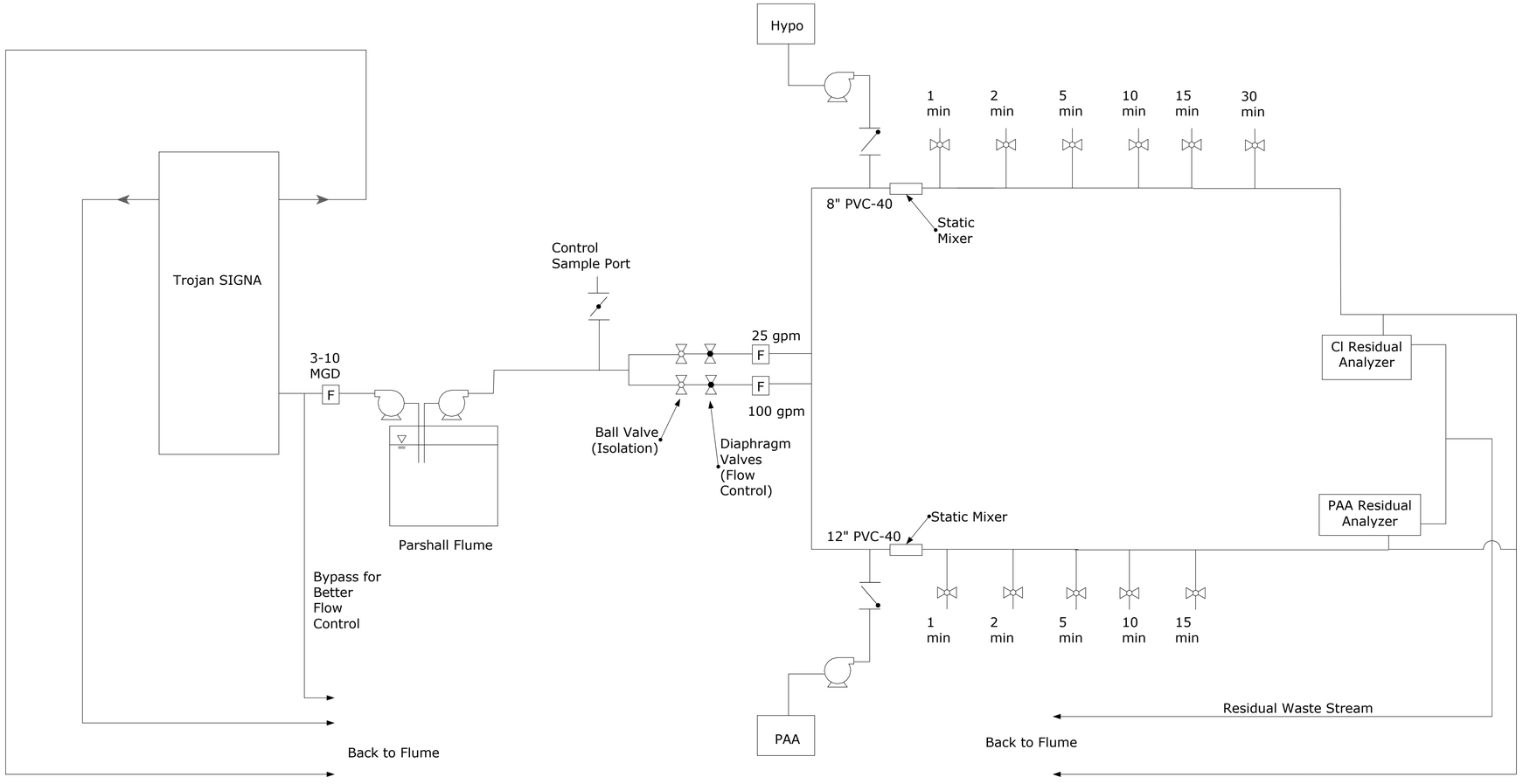
Figure 2-4 Chemical feed pump

Figure 2-5 Sample Tap

The UV disinfection pilot trailer was rented from Trojan Technologies. The system was housed in a semi-trailer near the Parshall flume. The TrojanSIGNA pilot was comprised of a stainless steel channel, a UV lamp bank containing eight Trojan solo lamps, an automatic lamp cleaning system, and an online UVT analyzer. The pilot unit is capable of treating up to 10 MGD when UVT values are at least 35%. Due to effluent UVT during the pilot period, flow was limited to about 7MGD. UV disinfected samples were collected using a dip sampler to grab samples directly from the channel, downstream of the UV lamps. The UV pilot system was fed from the inlet to the Parshall flume and discharged back into the effluent end of the Parshall flume structure. Flows ranged between 1MGD and 7MGD. A photograph of the TrojanSIGNA system is shown in **Figure 2-6**. A process flow diagram for the entire pilot system is shown in **Figure 2-7**.

Figure 2-6 TrojanSIGNA UV System

FIGURE 2-7
PROCESS FLOW DIAGRAM
PILOT SYSTEM AT MAXSON WWTP



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DRAWN BY: Josh Goldman
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE:

CDM Smith
555 17th Street, Suite 1100
Denver, CO 80202
Tel: (303) 383-2300

CITY OF MEMPHIS

MAXSON DISINFECTION PILOT

FIGURE 2-7
PROCESS FLOW DIAGRAM
PILOT SYSTEM AT MAXSON WWTP

PROJECT NO. 6016-83104
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The general procedures for disinfection tests were to set the PAA and hypochlorite feed pumps for specific feed rates to achieve targeted doses; the UV dose was set based on flow and UVT which was used to determine the lamp power setting for each experiment. After a stabilization period of approximately three average hydraulic retention times for the pilot system to reach steady state, control samples were analyzed for apparent color, UVT, TSS, *E. coli*, and DBPs in selected samples. Treated samples were analyzed for oxidant residual (for chemical oxidants), *E. coli* and DBPs in selected samples. The scope of the pilot was to characterize DBP formation potential for chlorine-based disinfection, but selected DBP samples were also run for PAA tests to confirm that DBP formation is not a concern. Color and UVT were not evaluated in the treated samples because the influence of disinfection method on the effluent color was not a stated objective of this study. Control aliquots were obtained from the control sample port prior to disinfection and disinfected samples were collected at either the 15 or 30 minute sample port for additional testing to establish the performance of the set chemical dose. The disinfected samples were tested in the field for chemical residual, pH and temperature. Approximately once per week, several samples were also collected for shipment to an external laboratory to test for DBPs; these samples were collected and shipped on ice to Test America. Samples were analyzed for dioxins, NDMA, and THMs.

The TrojanSIGNA UV pilot procedure was developed with the help of Trojan Technologies in order to verify applicability of the third-party validation that defines the reduction equivalent dose (RED) as a function of flow rate, lamp power, and UVT. For each experiment, UVT was measured and the system was set to a specific flow rate and lamp power. A RED was calculated based on difference between the concentration of *E. coli* in the disinfected sample and the control sample; the result was compared to the value predicted by the third party equation. A summary of the analytical methods used for testing is provided in **Table 2-1**.

Table 2-1 Analytical methods

Parameter	Responsible party	Method
pH	CDM Smith	pH probe
E. coli	CDM Smith	Standard Methods 922µ
TRC	CDM Smith	Hach DPD Kit
Total Residual PAA	CDM Smith	Chemetrics PAA Kit EPA Method µµ0.5
TSS	City of Memphis laboratory	Standard Methods 2540C
UVT, Apparent	CDM Smith	Single wavelength at 254nm using HACH DR5000
Color, Apparent	CDM Smith	Standard Methods 2420
Dioxins	CDM Smith (subcontract to specialty laboratory)	EPA Method 161µ
THMs	CDM Smith (subcontract to specialty laboratory)	EPA Method 524.1
NDMA	CDM Smith (subcontract to specialty laboratory)	EPA Method 8270
Particle size analysis	CDM Smith (subcontract to specialty laboratory)	Digital imaging using FlowCAM®

Figure 2-8 shows the preparation of an IDEXX tray for *E. coli* analysis, and **Figure 2-9** shows the IDEXX tray being sealed prior to incubation. After a 24-hour incubation period, IDEXX trays (**Figure 2-10**) are examined under a black light to determine which cells contain *E. coli*. A most probable number of *E. coli* is calculated based on the number of wells that fluoresce.

Figure 2-8 IDEXX tray preparation

Figure 2-9 IDEXX tray sealing

Figure 2-10 Incubated IDEXX trays

Section µ

Pilot Results

µ.1 Characterization of Maxson WWTP Effluent

The efficacy and efficiency of wastewater disinfection processes that could be implemented are integrally tied to effluent quality prior to disinfection. Applicability of chemical disinfection alternatives depends on oxidant demand, potential to form DBPs, and the presence of recalcitrant organic compounds that pass through the treatment process. The effluent water quality of the untreated (control) samples during the pilot testing period is summarized in **Table 3-1** along with the NPDES permit limits, TDEC water quality criteria, and historical performance, described in Section 2.

The strategy for implementation of the pilot study included consideration of timing to capture conditions when the lowest effluent quality could be tested. As a result, testing was targeted for late winter when temperatures are lowest and when plant staff has the most difficulty with plant operating conditions. Based on the effluent characterization data collected during the pilot and presented in Table 3-1, the effluent quality adequately reflected conditions that would provide information for developing engineering design criteria to meet permit compliance under the most difficult operating conditions.

In general the results for parameters tested for control samples during pilot testing showed the following:

- TSS during the pilot period were higher than historical averages for samples; while grab samples were not collected for BOD, the daily composites collected for permit compliance during this same period were also higher than reported in historical data. Specifically, the average BOD during the pilot period was 51 mg/L as compared to an average of 30 mg/L for the period between 1/1/2008 and 5/31/2013.
- *E. coli* concentrations measured in pilot samples were within the range of historical concentrations. During the pilot period, the average *E. coli* concentration was 2.6 x 10^5 cfu/100 mL compared to 7.3 x 10^5 cfu/100mL recorded between 9/14/2010 and 7/11/2013.
- Color and UVT, which are parameters that can be used as indicators of the characteristics of organic carbon in the effluent, were measured; color during the pilot study was higher than historical data and UVT measured during the study was substantially lower than data previously reported in Table 1-1.

DBPs including dioxins, trihalomethanes (THMs) and N-nitrosodimethylamine (NDMA) were measured; two dioxin congeners were detected at least once in the undisinfected effluent, and one OCDD, persisted into the disinfected water. Neither THMs nor NDMA were detected in any control sample.

Table µ-1 Secondary Effluent Water Quality during Pilot Testing

Parameter		Units	NPDES Permit Limits[1]		TDEC Water Quality Criteria	Average Value during Pilot Test Period	Historical daily average concentration[2,µ]
			Monthly	Daily		µ/1 -4/5	
E. coli		cfu/100mL	126 (geomean)	487	-	2.6×10^{5}	$7.\mu \times 10^{5}$
BOD		mg/L	42	84	-	51[5]	µ0
TSS		mg/L	48	96		42[5]	µ0.µ
Color, Apparent, Average		PtCo Units	-	-	-	562	401
UVT, Apparent, Average		% Transmittance	-	-	-	17	27
NDMA		µg/L	-	-	µµ	0	-
THMs	Bromoform	µg/L	-	-	1400	0	-
	Chlorodibromomethane	µg/L	-	-	1µ0	0	-
	Chloroform	µg/L	-	-	4700	0	-
	Dichlorobromomethane	µg/L	-	-	170	0	-
Dioxins, Total[4]		µg/L	0.000001	0.000001	0.000001	0	-

[1] Maximum average unless otherwise noted.
[2] *E. coli* period of record is 9/14/2010 – 7/11/201µ.
[µ] TSS period of record is 1/2008 – 5/201µ.
[µ] Color, UVT period of record is 1/2010 – 5/201µ.
[4] Total dioxins is the sum of all dioxin and dibenzofuran isomers after multiplication by Toxic Equivalent Factors (TEFs).
[5] Average value compiled from plant MOR data during piloting period.

µ.2 Sodium Hypochlorite Test Results

Chlorination, by bulk liquid hypochlorite is a widely used disinfection method and could be used at the Maxson WWTP with construction of a chlorine contact basin and chemical feed and storage facilities. New instrumentation and programming would be required for process control and integration into the existing plant control system. For piloting at the Maxson WWTP, a 12.5% sodium hypochlorite solution was obtained from Ideal Chemical and fed using a Pulsatron Series MP diaphragm pump through a static mixer into the pilot reactor. The applied doses tested ranged throughout the study from 9 mg/L to 36 mg/L as shown in **Figure 3-1.**

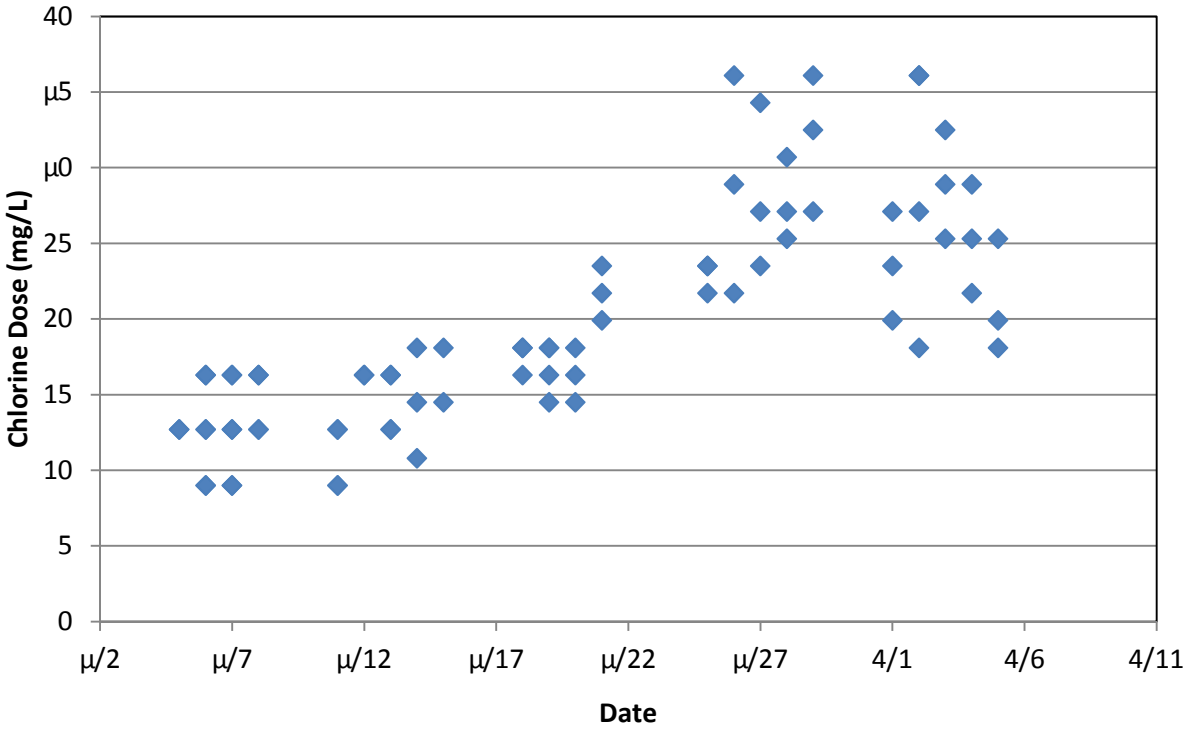


Figure µ-1 Chlorine dose range for pilot period

µ.2.1 Chlorine, Demand, Residual and *E. coli* Disinfection

There are a number of disinfection process control strategies that can be employed to manage a chlorine based (here, sodium hypochlorite) disinfection system. Because there is a lag time in obtaining bacterial inactivation results, there is no "on-line" method that provides direct process control for disinfection. One method that has been used to control chlorine disinfection processes is to use chlorine residual which can be linked to process performance by developing an understanding of the process through testing.

Inactivation kinetics of chlorine disinfection has been studied extensively, and has generally been described with expressions that combine process parameters such as disinfectant dose, contact time and microbial concentrations. The Chick–Watson formula is the oldest model that has been used and is based on the product of residual disinfectant concentration (C) and contact time (t).

$$log\left(\frac{N}{N_0}\right) = -L_S C^n t$$

In the Chick–Watson formula N_0 and N are the initial and final (i.e., after time t) microbial counts, L_S is the specific coefficient of lethality (i.e., the disinfection efficacy when C and t are equal to 1) n is the dilution coefficient, which depends on the specific disinfectant, pH and temperature, and it is often close to 1 for chlorine based disinfection and can be applied successfully when treating water that has a consistent chemical demand.

The model can be applied to wastewater disinfection with chlorine when there is certainty that a single mode of disinfection is used. With respect to chlorine disinfection, there are two different forms of chlorine that can be used to provide disinfection, either free chlorine or combined chlorine (or chloramines). When sodium hypochlorite is applied to wastewater effluent, hypochlorous acid is produced; and, if ammonia is present in the treated effluent at concentrations greater than about 2.0 mg/L, hypochlorous acid will react with ammonia (NH_3) to form chloramines:

$$NH_3 + HOCl \rightarrow NH_2Cl\,(monochloramine) + H_2O$$

$$NH_2Cl + HOCl \rightarrow NHCl_2\,(dichloramine) + H_2O$$

$$NHCl_2 + HOCl \rightarrow NCl_3\,(nitrogen\ trichloride) + H_2O$$

While free chlorine (as hypochlorous acid) is a more powerful oxidant and has faster bacterial inactivation kinetics, achieving free chlorine disinfection depends on the amount of ammonia and organic compounds in the effluent. This process is well documented, and the breakpoint chlorination process is graphically depicted in **Figure 3-2** (Metcalf & Eddy, 2003).

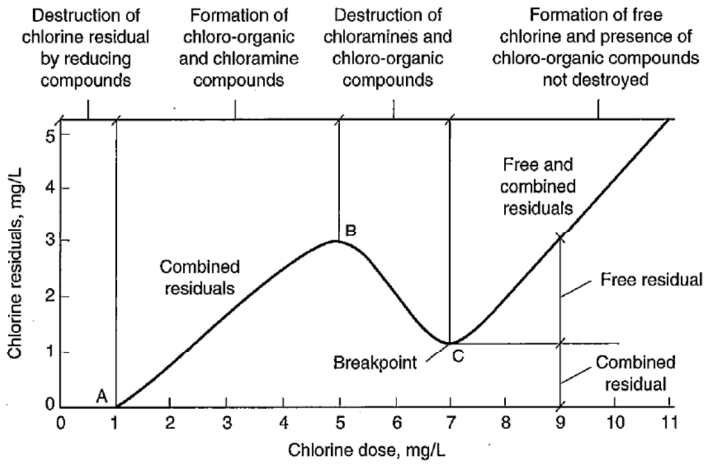


Figure µ-2 Breakpoint chlorination curve (Metcalf & Eddy, 200µ)

It is important to note no significant free chlorine residual is produced unless the breakpoint is reached. Thus, in the case of the Maxson WWTP, it would not be feasible to overcome the ammonia concentrations in the effluent to achieve breakpoint chlorination because the facility is not required to nitrify. While chloramines are slower-reacting than free chlorine, they still provide excellent pathogen inactivation, given adequate contact time. Additionally, chloramination can also significantly reduce

the potential for production of DBPs. However, process control for a chloramine system, particularly for effluent with a complex composition, can be quite challenging.

Process control for chlorine disinfection is typically based on total residual chlorine (TRC) control. The challenge in using this approach for chloramination is that for plants with complex effluent quality, chlorine reactive compounds, such as organic-nitrogen, nitrites, color, or other compounds, may exert a high chlorine demand prior to establishing a measurable residual. Peng (2009) showed that an organic-nitrogen concentration above 2-mg/L would form organo-chloramines (a.k.a. chloro-organic compounds), which although they contribute to the formation of TRC have negligible disinfecting strength. Additionally, organic color may be bleached by chlorine in competing reactions with formation of chloramines and can consume significant concentrations of chlorine. There are other inorganic reactions of chlorine with reduced substances such as sulfides, sulfites, nitrites, ferrous iron, and reduced manganese compounds which react with both free chlorine and combined chlorine. These reactions usually occur within the first minute at which point there is no measureable residual. As a result, it is important to conduct site specific testing to determine the target residual that will allow a facility to utilize TRC for effective process control (Szerwinski, et al., 2012).

Pilot data was treated using the Chick-Watson model to determine kinetic parameters for determining design criteria for a chloramination disinfection system. When data were analyzed, there was a group of data that could not be fit with the model, as shown in **Figure 3-3**. The analysis showed that the model predicted significantly higher inactivation rates than were observed for some samples.

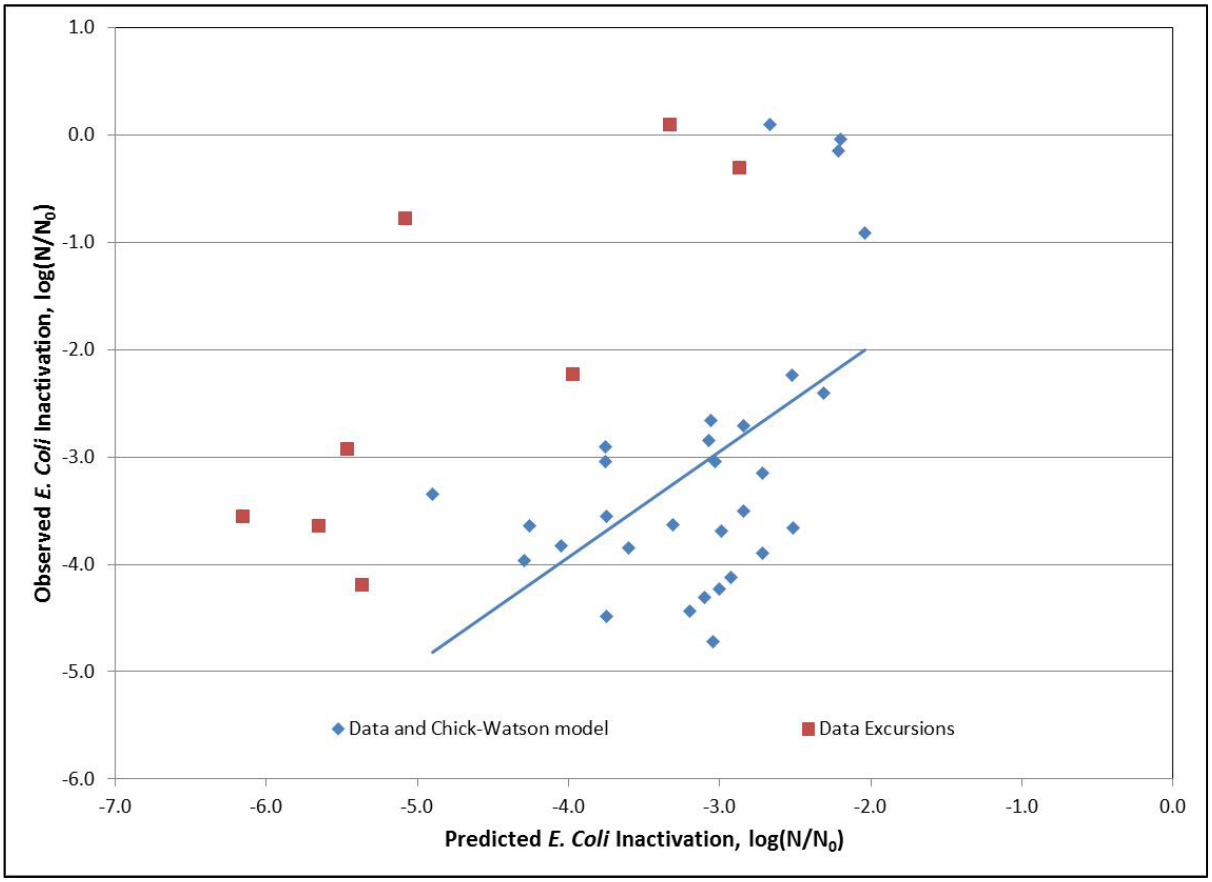


Figure µ-µ Observed versus predicted disinfection performance using the Chick-Watson model

Data were reviewed to determine if the samples that were excursions from this normal disinfection model could be correlated to another effluent parameter measured during the study. It was determined that the majority of data that were excursions from the model were data collected at 30 minutes. Closer evaluation of the data showed that there was no additional benefit of time in terms of bacterial inactivation and that the inactivation generally occurred during the first 15 minutes of contact time. However, this was not always the case, and use of this approach for process control could be challenging.

In order to establish an approach to providing consistent process control, bacterial inactivation results were also plotted as a function of TRC (showing both 15 and 30 minute data) in **Figure 3-4**; a best fit was plotted for the 15 minute data (maximum flow design conditions) and compared to the operational inactivation requirement to set the average operating dose as described in Section 1.4.1. Based on the fitted data, a target residual of 10 mg/L should be used to meet the operational requirements for disinfection.

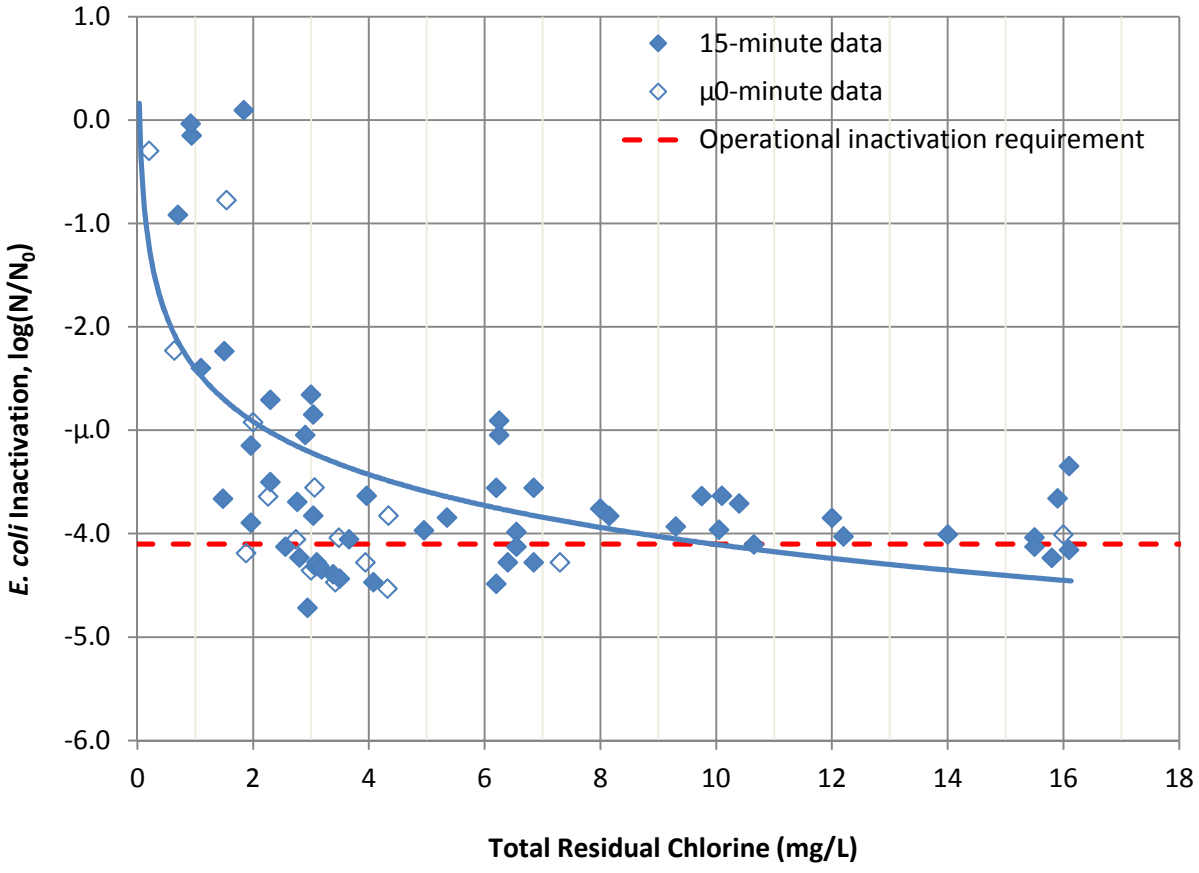


Figure µ-4 *E. coli* inactivation as a function of chlorine residual

µ.2.2 Chlorine Design Dose for *E. coli* Disinfection

In order to establish the basis for design, that is the average, minimum and maximum feed rates to aid in sizing chemical storage facilities and selection of pump sizes, it is necessary to determine the range of chlorine doses that provide the required residuals as described in the previous section. To determine the chemical dose that would need to be applied to achieve the target disinfection rates, the

oxidant demand must be satisfied. The oxidant demand which is operationally defined as the applied dose minus the residual can be added to the target residual to establish the design dose.

Chlorine demand data as a function of color were plotted for doses less than 25 mg/L that provided measurable residuals **(Figure 3-5)**. The 25 mg/L cutoff was used because these concentrations are beyond those that would be required to provide disinfection and more importantly, the interparticle chemical concentration gradients at these concentrations eliminate diffusion boundaries that impact disinfection efficacy and these factors cannot be accounted for in these tests. Chlorine demand data were similarly plotted as a function of UVT **(Figure 3-6)**. In the case of color, there was no clear relationship between the effluent color and chlorine demand. For UVT, there is a slight, apparent relationship between effluent UVT and chlorine demand, however, this relationship is weak and not statistically significant.

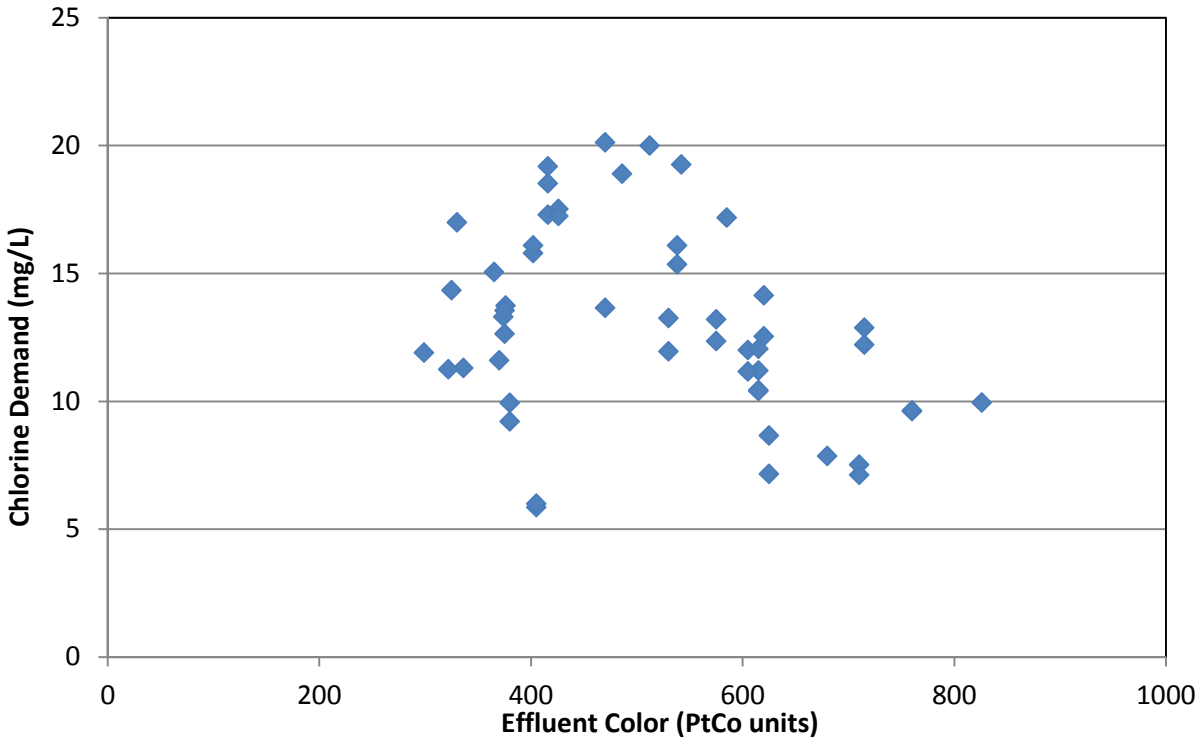


Figure µ-5 Chlorine demand as a function of color

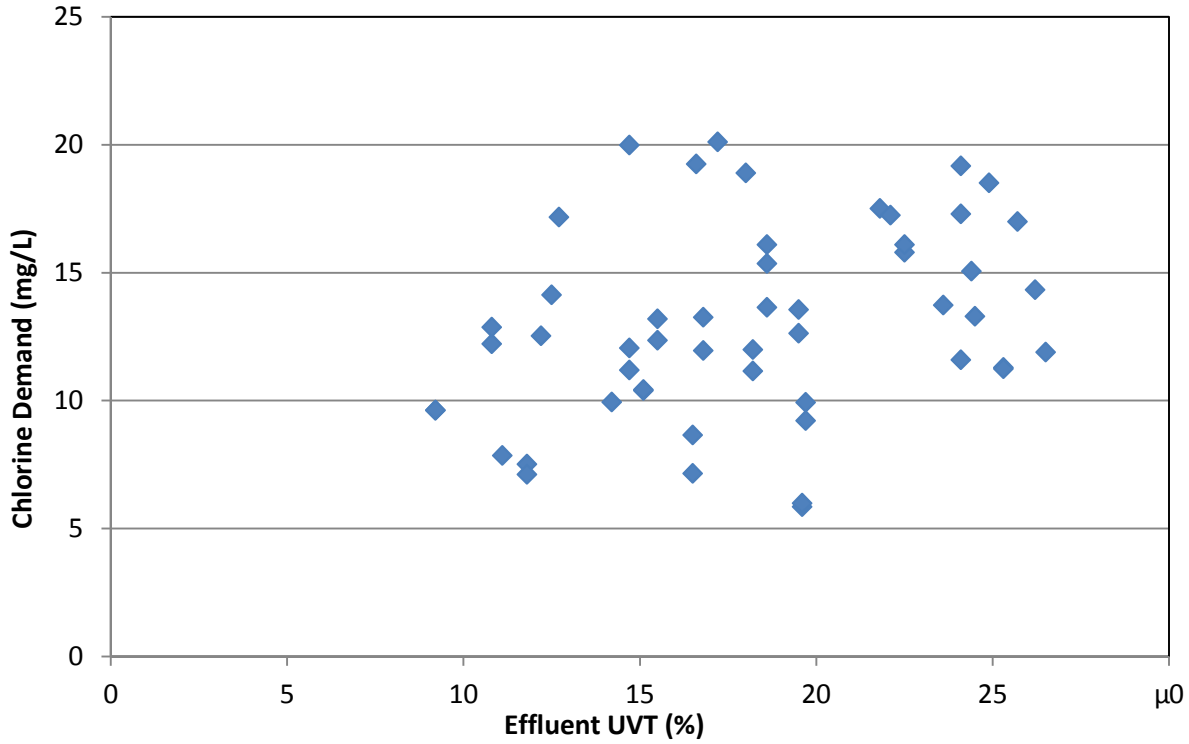


Figure µ-6 Chlorine demand as a function of UVT

Chlorination by application of bulk sodium hypochlorite was inconsistent for achieving required *E. coli* inactivation, (**Figure 3-7**). Results showed that when inactivation is achieved, the process is generally accomplished within the minimum 15 minutes contact time required by the *Tennessee Design Criteria for Sewage Works* for peak flow conditions, when doses are applied that provide a residual that would consistently be in excess of 10 mg/L. The challenge is that there are no clear process control parameters, other than total residual chlorine to help indicate when high chlorine demands would be observed. Thus, due to the highly variable nature of the efficacy of the process, it is recommended to set the sodium hypochlorite design dose at 20 mg/L for the purposes of this evaluation.

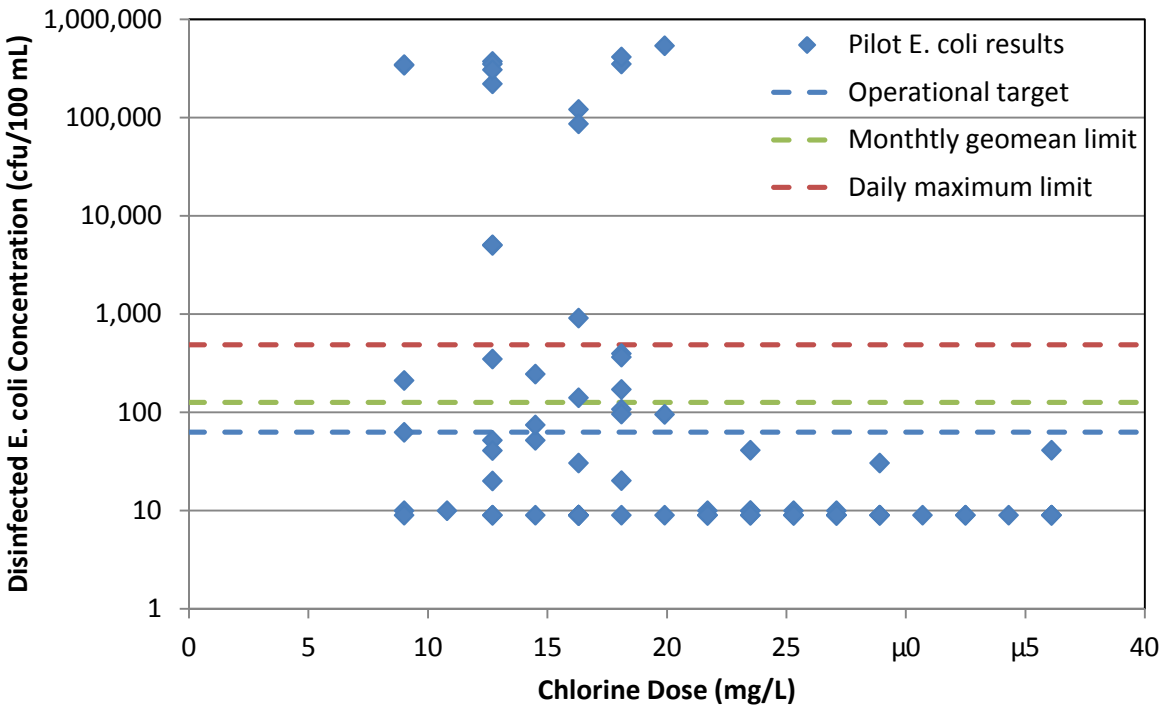


Figure µ-7 *E. coli* results as a function of applied chlorine dose

µ.µ Peracetic Acid Test Results

Disinfection, by bulk liquid PAA is relatively new method of municipal wastewater disinfection in the US. However, this method of disinfection is gaining interest due to its ability to provide bacterial inactivation performance at costs competitive to other mature technologies without the formation of regulated DBPs. PAA has been applied to the food, beverage, medical and pharmaceutical industries as a disinfectant for many years and has been demonstrated for municipal wastewater disinfectant in Europe with PAA disinfection being applied for effluent reuse (with an *E. coli* limit of 10 cfu/100mL) at the largest WWTP in Milan, Italy (Nosedo WWTP with an average flow of 110 mgd) since 2006 as shown in **Figure 3-8**.

PAA disinfection at the Maxson WWTP, by application of bulk liquid PAA, would require the construction of a new contact basin and construction of new facilities to house chemical storage and feed equipment, which could be provided as part of a PAA solutions package from FMC. For piloting at the Maxson WWTP, a 15% PAA solution (VigorOx II) and a diaphragm pump were provided by FMC for testing. The PAA solution was pumped into the pipe reactor through a static mixer to achieve doses ranging from 4.5 to 15 mg/L as shown in **Figure 3-9.**

Figure µ-8 Nosedo WWTP, Milan Italy (image from: http://www.google.com/imgres?q=nosedo+milano+wwtp&um=1&sa=N&biw=1175&bih=645&hl=en&tbm=isch&tbnid=gCARV5pXzQnHKM:&imgrefurl=http://www.bonatti.it/Projects/Nosedo-Waste-Water-Treatment-Plant-Milan&docid=ivw6zuCUXowPKM&imgurl=http://www.bonatti.it/var/bonatti/storage/images/media/images/nosedo-waste-water-treatment-plant_1/9247-1-eng-GB/Nosedo-Waste-Water-Treatment-Plant_1_imagelarge.jpg&w=550&h=µ68&ei=SH_MUdPsOYLC4AOvmYDgCA&zoom=1&iact=hc&vpx=2&vpy=1µ0&dur=297&hovh=184&hovw=275&tx=1µ8&ty=106&page=1&tbnh=140&tbnw=214&start=0&ndsp=20&ved=1t:429,r:0,s:0,i:81)

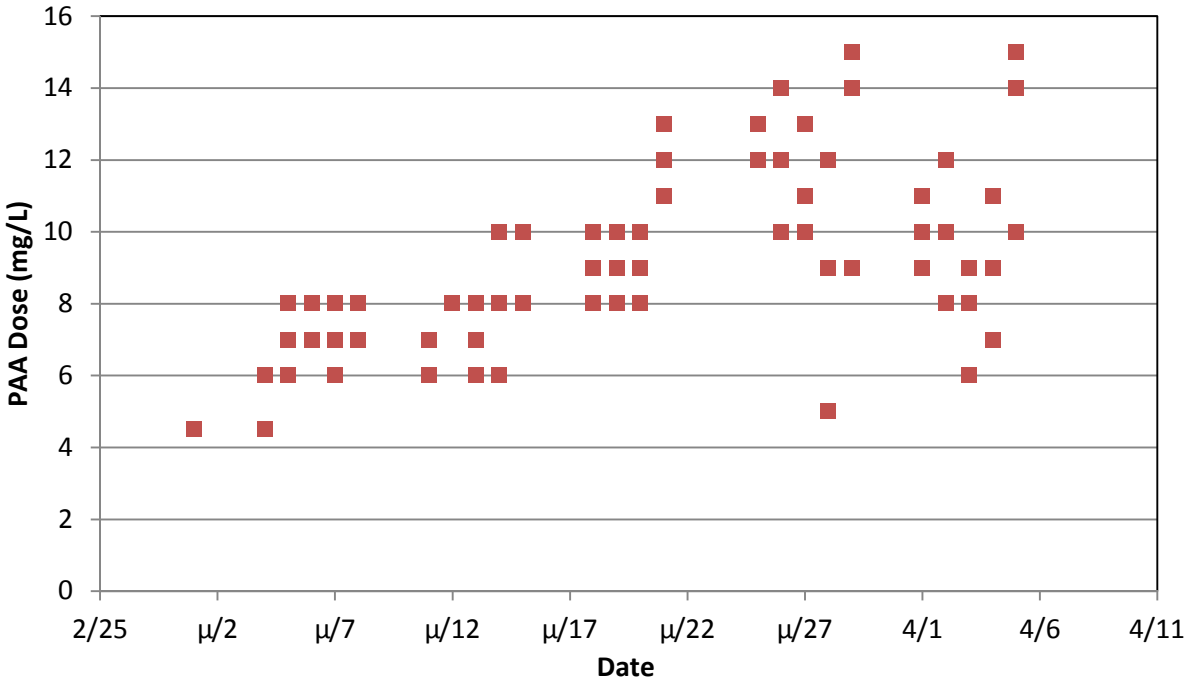


Figure µ-9 PAA dose range for pilot period

µ.µ.1 Peracetic Acid Residual, and *E. coli* Disinfection

There are a number of disinfection process control strategies that can be employed to manage a PAA disinfection system, but in general PAA has been operated using a dose pacing methodology. If the oxidant demand is variable, it can be paced using total residual PAA concentration, similar to use of TRC for chlorine disinfection. PAA residual control should be linked to site-specific performance data through testing, as conducted during this study. These site-specific water quality parameters could include color, chemical oxygen demand (COD), UVT, etc.

The "CT" approach that is traditionally used for chlorine disinfection as previously described for chlorination is not fully adequate to assess the effectiveness PAA disinfection because of differences in chemical half-lives and, as a result, it necessary to capture the decay kinetics and combine these with a valid microbial inactivation model to describe the process. There are a number of models that have been developed to address this effect and most are generalizations of the Chick–Watson formula. Among the published models, Hom's model is probably the most widely used to account for deviations from the first-order kinetics of the Chick-Watson formula.

$$log\left(\frac{N}{N_0}\right) = -kC^n t^m$$

In Hom's model, m is used to account for either shoulders or tailing which may occur from a number of different factors, but with respect to PAA disinfection, and it can be used to account for the shorter half-life of PAA. The model has been validated in several studies, showing that Hom's model is the most appropriate for describing PAA disinfection of secondary wastewater effluent for coliform organisms (Rossi et al., 2007; Azzellino et al., 2011). These studies were evaluated because of the need to address process control for WWTPs in Italy that had switched to PAA disinfection to meet the rigorous Italian standards for DBPs. For data collected through laboratory testing at the Nosedo

WWTP previously described, Antonelli et al. (2011) demonstrated that the PAA performance was consistent with the mathematical representation of the variables where:

- k is the disinfection rate constant otherwise known as the specific coefficient of lethality and depends on the target organism (here, *E. coli*) and other factors such as bacterial association with TSS.
- When n < m, t (contact time) is the primary factor affecting inactivation and longer contact times will provide additional disinfection benefit.
- When n ~ m, and t and PAA residual are similar in their effect on inactivation.
- When n > m, chemical residual overrides contact time with respect to disinfection efficacy.
- When m < 1, there can be a tailing-off behavior at very long contact times.

Uncensored bacterial counts and residual measurements (i.e., results were greater than non-detection, which cannot be interpreted in the analysis of the model) were analyzed using Hom's model. The predicted versus observed results for bacterial inactivation are shown in **Figure 3-10**. The detection limit for measurement of *E. coli* was 10 cfu/100 mL, the lowest measurable PAA residual was 0.6 mg/L, and the and highest applied PAA dose used in the analysis 10 mg/L. Hom's model data was adequate for representing the data collected during the study, and there were no clear outliers when data were censored as described.

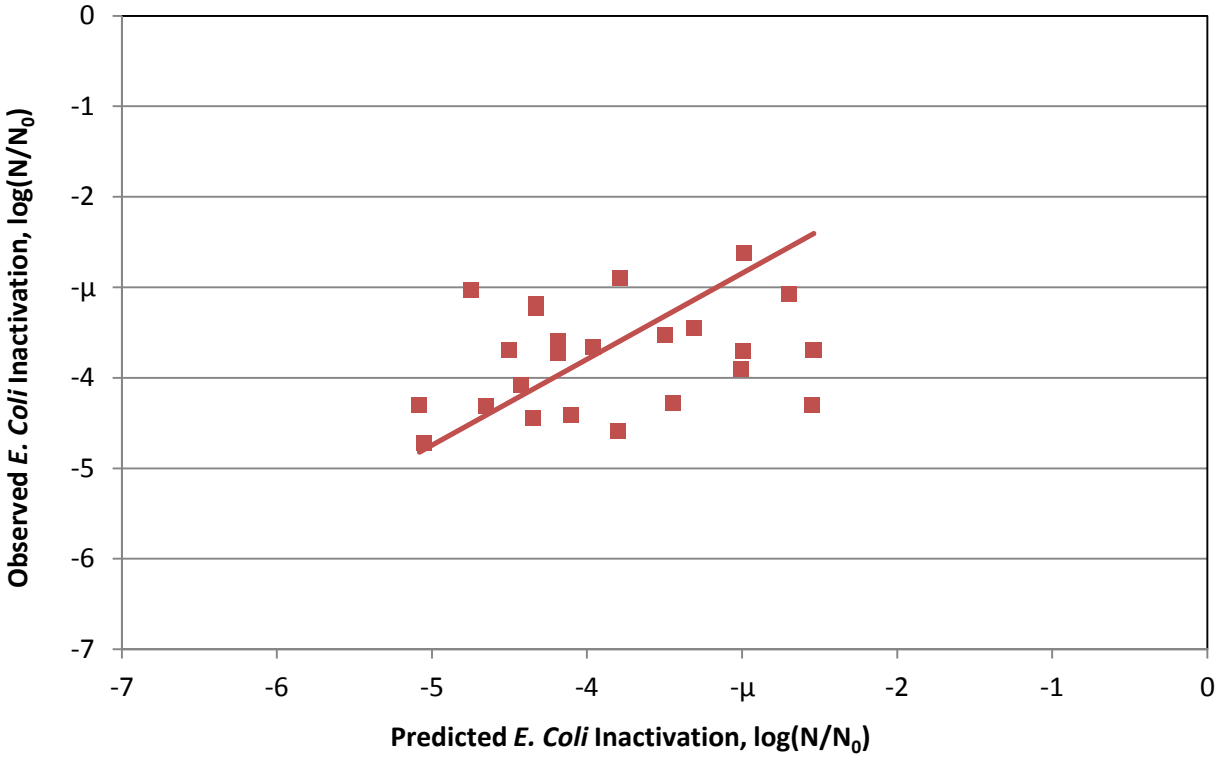


Figure µ-10 Observed versus predicted disinfection performance using Hom's model

The kinetic parameters determined using Hom's model are k = 0.6, n = 0.5 and m = 0.52 which are consistent with other studies of *E. coli* inactivation. Thus, data may be interpreted, with n ~ m, that contact time and residual are equally important factors affecting inactivation and longer contact times

will provide additional disinfection benefit. When m < 1, there can be a tailing-off behavior at very long contact times so there is a limit to which the additional benefit could be observed. In order to determine whether an increased contact time (from 15 to 30 minutes) would provide additional disinfection benefit, additional bench testing was conducted on a sample collected on July 22, 2013. Data from this test date for several PAA doses and contact times are shown in **Figure 3-11.** The data shows, as anticipated, that at PAA doses above 4 mg/L, there is a clear benefit to an increased contact time.. As a result, Hom's model developed based on 15 minute pilot data could be applied to predict average performance at up to 30 minutes contact time.

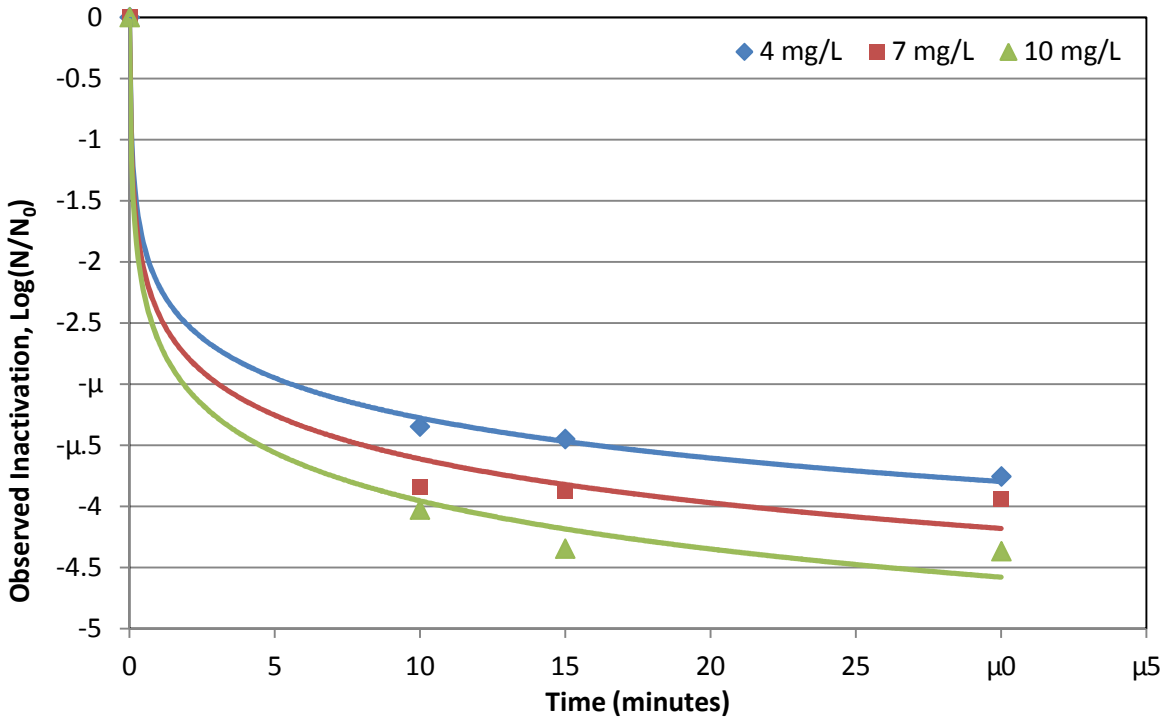


Figure µ-11 Bench test results for disinfection of Maxson effluent at 10, 15 and µ0 minute contact times, for three PAA doses (testing conducted by FMC in support of cost proposal for PAA)

µ.µ.2 PAA Design Dose for *E. coli* Disinfection

In order to establish the basis for design, that is the average, minimum and maximum feed rates to aid in sizing chemical storage facilities and selection of pump sizes, it is necessary to determine the range of PAA doses that provide the required inactivation rates as described in the previous section. To determine the chemical dose that would need to be applied to achieve the target disinfection rates, the target dose was determined using the model developed in this analysis. Using the average effluent *E. coli* concentration and the operational target of 63 cfu/100 mL for a 15 minute contact time, a calculated target residual of 3.0 mg/L must be achieved as shown in **Table 3-2**. In order to achieve these target residuals, the oxidant demand must be satisfied and this value must then be added to the target residual to establish the design dose. Because the target residual concentration required for disinfection is > 2.0 mg/L, quenching (the equivalent of dechlorination for chlorine) would be required under the current draft NPDES permit. The estimated design dose was determined by adding the oxidant demand of 6.0 mg/L, which was determined by calculating the average over the entire set of pilot data, to the target residual.

Table µ-2 Calculated PAA residual and dose to meet target *E. coli* concentration at 15 minutes contact time

Target Effluent Condition, N (cfu/100 mL) =	126			6µ		
Effluent *E. Coli*, N_0 (cfu/100mL)	$\log(N/N_0)$	C_{168}	Dose	$\log(N/N_0)$	C_{84}	Dose
500,000	-µ.60	2.µ2	8.28	-µ.90	2.71	8.67
1,000,000	-µ.90	2.71	8.67	-4.20	µ.12	9.08
2,000,000	-4.20	µ.12	9.08	-4.50	µ.57	9.5µ

If the average contact time is longer than 15 minutes the data could be extrapolated using Hom's model, as supported by data presented in Figure 3-11. Under this condition, it is possible to reduce the target residual under average operating conditions to less than 2.0 mg/L which would allow the facility to be operated without residual quenching, as shown in **Table 3-3.**

Table µ-µ Calculated PAA residual and dose to meet target *E. coli* concentration at µ0 minutes contact time

Target Effluent Condition, N (cfu/100 mL) =	126			6µ		
Effluent *E. Coli*, N_0 (cfu/100mL)	$\log(N/N_0)$	C_{126}	Dose	$\log(N/N_0)$	$C_{6µ}$	Dose
500,000	-µ.60	1.19	7.15	-µ.90	1.µ9	7.µ5
1,000,000	-µ.90	1.µ9	7.µ5	-4.20	1.60	7.56
2,000,000	-4.20	1.60	7.56	-4.50	1.8µ	7.79

To determine whether there was a process control parameter that could be used to predict chemical demand, similar to the analysis conducted for chlorine, PAA demand was evaluated with respect to both color and UVT. In both cases, there was no apparent relationship between oxidant demand and color or UVT; and the graphs have not been shown.

Figure 3-12 shows E. coli inactivation as a function of PAA dose, and **Figure 3-13** shows E. coli inactivation as a function of PAA residual. These data represent the difficult operating conditions that were experienced during the pilot period. **Figure 3-13** indicates that a higher target residual than predicted by the Hom's model may be required to achieve disinfection compliance. The recommended design dose would be in excess of 10 mg/L as shown in **Figure 3-12**. Using the target residual of 7.0 mg/L as indicated in **Figure 3-13**, a design dose of 13 mg/L can be established by adding the average PAA demand as described in the previous paragraphs. Thus, due to the highly variable nature of the efficacy of the process, it is recommended to set the PAA design dose at 13 mg/L.

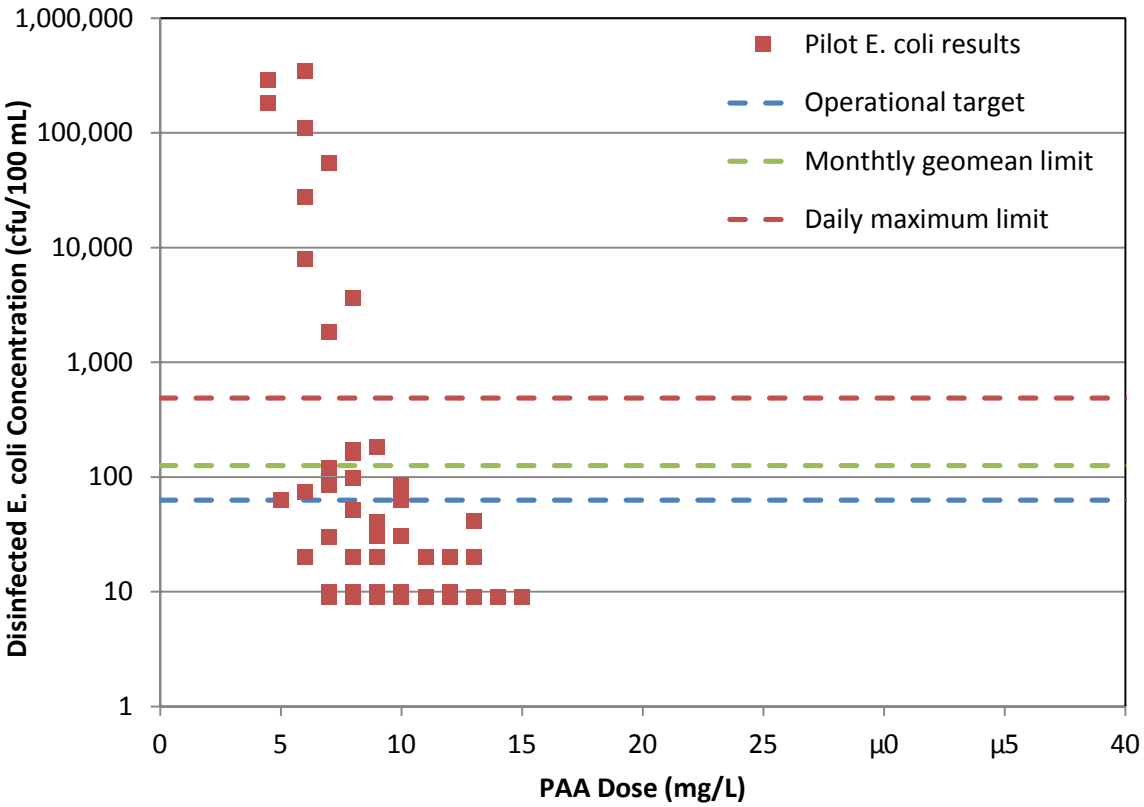


Figure µ-12 *E. coli* results as a function of applied PAA dose at 15 minutes

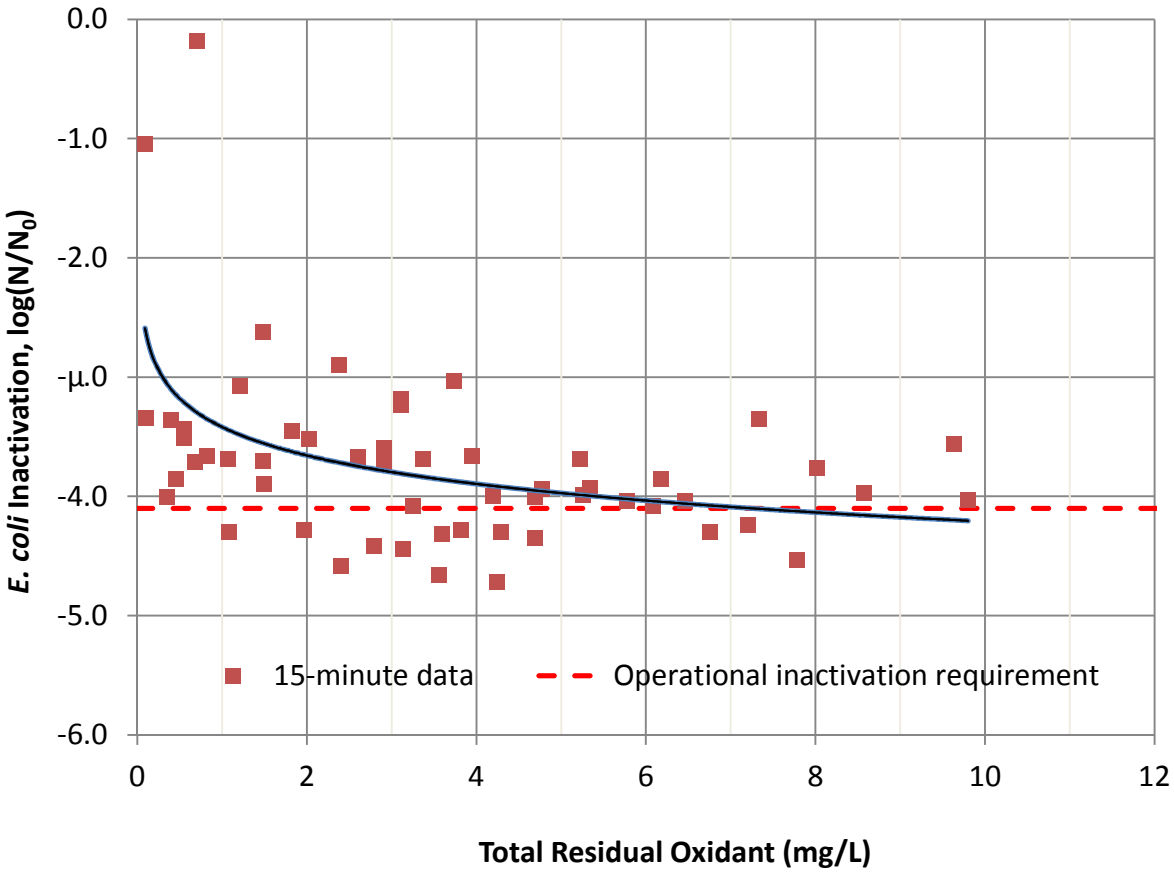


Figure µ-1µ *E. coli* inactivation as a function of PAA residual

Disinfection by application of PAA was demonstrated to be effective for achieving required *E. coli* inactivation. Results show that inactivation is accomplished within the minimum 15 minutes contact time at peak flow, and there is additional benefit that is obtained with longer contact times. Thus, for the purposes of this evaluation it is recommended that the chemical contact time requirements for PAA be designed to be equivalent to the required contact time for a chlorine disinfection system.

µ.4 Disinfection By-Products

As noted in Section 1.4.2, testing was conducted during the pilot study to evaluate the potential formation of DBPs. While the concern regarding DBP formation is primarily linked to use of chlorine based disinfection methods, some testing was also conducted on samples treated with PAA to confirm that DBP formation would not be a concern. Testing showed that there was no NDMA detected in any sample tested. Results for dioxins and THMs are shown in **Figures 3-14** and **3-15**.

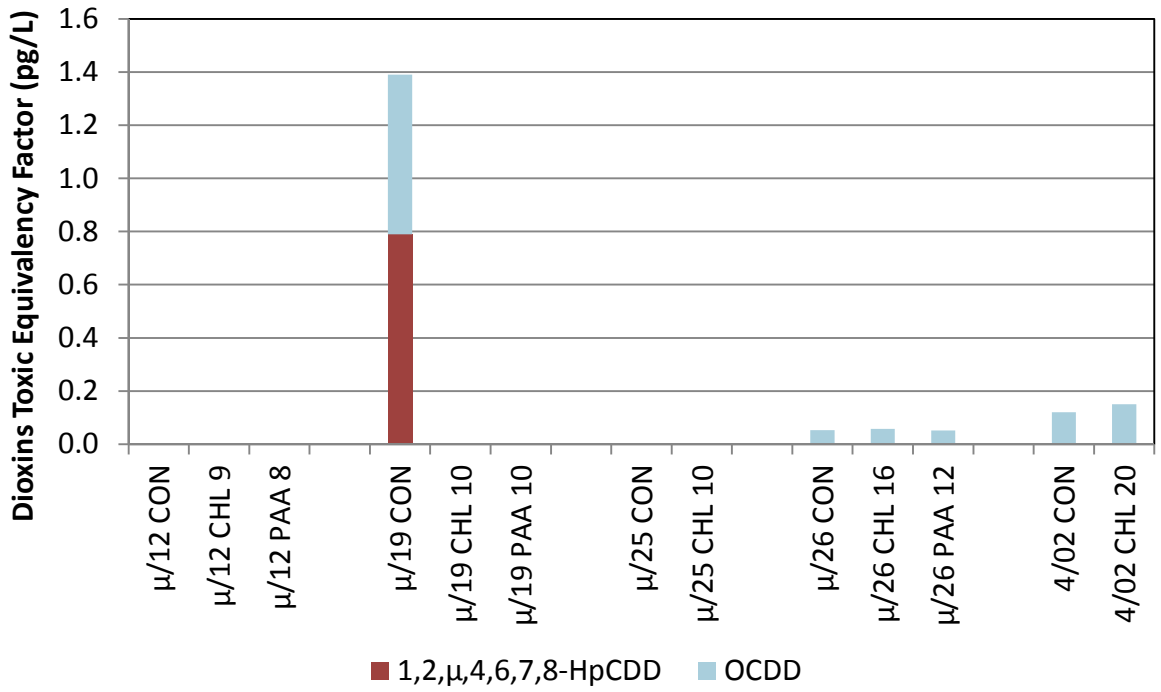


Figure µ-14 Toxicity equivalents for control and disinfected samples collected during pilot testing

Note: x-axis labels contain the date of the test, the type of disinfectant
No bar indicates that the constituent was not detected.
(CHL – hypochlorite, PAA – peracetic acid, CON - control (no disinfectant). All doses in mg/L).

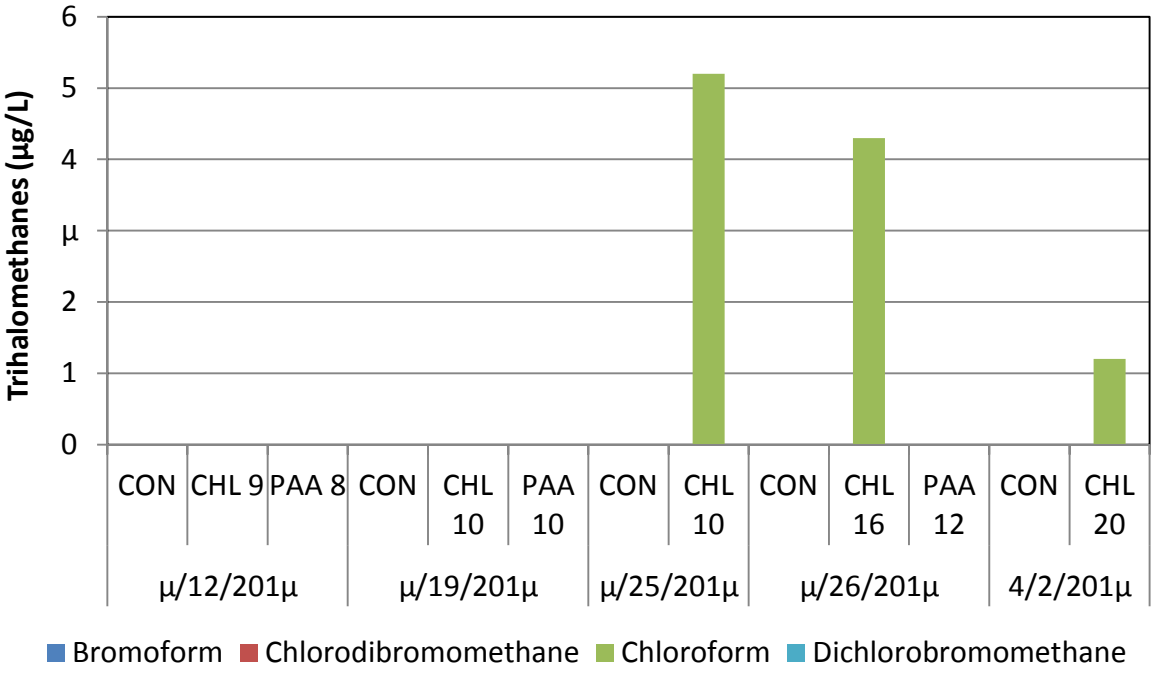


Figure µ-15 TTHM results for control and disinfected samples collected during pilot testing

Note: x-axis labels contain the date of the test, the type of disinfectant
No bar indicates that the constituent was not detected.
(CHL – hypochlorite, PAA – peracetic acid, CON - control (no disinfectant). All doses in mg/L).

Dioxin test results showed that one congener, octachlorodibenzo-*p*-dioxin (OCDD), was present in the treated effluent at less than permit limits on three dates and the compound persisted through the disinfection treatment process on two events. In the test, performed on March 19, 2013, 1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin (HpCDD) was detected in the undisinfected effluent, but it did not persist into the disinfected effluent. All other detections of dioxin compounds were less than the permitted limit of 1 pg/L.

With respect to trihalomethane compounds, no chloroform was present in any control samples. On three dates, March 25, 2013, March 26, 2013, and April 2, 2013 chloroform formation was noted with addition of high doses of chlorine. No chloroform formation was associated with PAA addition. In all cases, the resulting concentrations of chloroform were orders of magnitude lower than the instream water quality criteria of 4,700 ug/L.

µ.5 UV Disinfection Test Results

UV inactivation of microorganisms is a biophysical process; in practice, the primary germicidal activity occurs at a UV light wavelength of 254 nm. UV light at this wavelength alters the DNA of microorganisms and when sufficient UV dose is applied, microorganisms are rendered incapable of reproducing, effectively inactivating them. Thus, sizing of any UV disinfection system is based on delivering a required UV dose, which is a function of the UV intensity and the exposure time that wastewater is retained in the UV reactor. The equation used to calculate UV dose is shown below:

$$\text{UV Dose} = I \times t$$

Where: I = UV intensity, in milliwatts per square centimeter (mJ/cm^2)
t = exposure time, in seconds (s)
UV Dose, in mJ/cm^2 or milliJoules per square centimeter (mJ/cm^2)

The actual UV intensity and exposure time required to deliver the necessary dose are a function of the UV system, operating parameters and water quality. Exposure time is ideally the average hydraulic retention time within the UV reactor (or the reactor volume divided by the flow rate). The actual exposure time is a function of reactor volume, flow rate, mixing conditions within the reactor and extent of short-circuiting.

Water quality has the greatest effects on performance of a UV system because it can alter the UV intensity delivered within the reactor and, consequently, the UV dose received by the organisms in the wastewater. The most important water quality parameters are UVT and TSS concentration and TSS particle size distribution. UVT is the percentage of UV light, at 254 nm wavelength that is not absorbed (i.e. transmitted) after passing through a 1-centimeter water sample. As UV light passes through wastewater its intensity is attenuated by some substances. The relationship between UV intensity and transmittance is directly proportional, i.e., the higher the transmittance the higher the intensity available. TSS will absorb and scatter UV light, effectively lowering UVT. Additionally, the size of these solids affects the disinfection process; large suspended solids have the capability of screening or shading the target microorganisms, preventing them from receiving their required UV dose with larger particles having a higher impact. Thus, there is a generally accepted practical upper limit of TSS that can be effectively treated by UV disinfection of 30 mg/L. And, in the case of the equipment used in this study, Trojan Technologies will only guarantee process performance of their system in effluent that never exceeds 30 mg/L TSS.

µ.5.1 Establishing UV Dose

T1 is a nonpathogenic virus that is used in the validation of UV systems to approximate their effectiveness against target organisms such as E. coli. UV doses are often described as reduction equivalent doses (RED) meaning the UV dose that would inactivate a given amount of validation organism such as T1. In general, disinfection of E. coli in a typical secondary effluent requires a T1 reduction equivalent dose (RED) of 15 - 20 mJ/cm2 to meet a 126 cfu/100 mL as a monthly geometric mean. However, there can be site specific factors that impact the effective dose and these are primarily related to the characteristics of the TSS particles in the effluent, as described above. Thus, in order to estimate the site-specific dose to meet disinfection compliance, a laboratory test called a collimated beam study should be conducted over a range of plant operating conditions. The collimated beam study involves collection of an undisinfected wastewater sample and exposing the sample, in a continuously stirred reactor (usually a petri dish), to increasing UV doses. The target microorganism is measured after each dose is applied and the results are plotted to establish the target dose.

Collimated beam tests were run throughout the pilot study. Results from the collimated beam tests conducted during the pilot study are plotted along with the data from the bench test analysis conducted in September 2012 (CDM Smith, December 2012) in **Figure 3-16**. Results showed that, in general, *E. coli* inactivation below the daily maximum limit of 487 cfu/100 mL could be easily achieved at relatively low doses, from approximately 7 – 15 mJ/cm^2 (see green circles in Figure 3-16). However, as the target effluent *E. coli* concentrations decrease to 126 cfu/100mL which is the monthly geometric mean and 63 cfu/100mL which has been set as an operational target, there is a greater variability in the required design dose (as shown by the brown and red circles in Figure 3-16).

Thus, in order to consistently achieve the *E. coli* operational target, a design dose of as high as 37 mJ/cm^2 could be required. However, it is important to note that the TSS concentrations of samples tested were all in excess of 30 mg/L with the exception of three samples collected on September 17 and 18, 2012 and a third sample on March 19, 2013. Thus, in many cases, the treatment efficiency was better than expected; however, there were other samples that would require in excess of 19 mJ/cm^2, which is the design dose recommended by Trojan if a TSS concentration consistently below 30 mg/L could be achieved.

It is important to note that the pilot testing was conducted during the most difficult operational period of the year to determine the feasibility of providing bacterial compliance using UV disinfection. Results from this study clearly indicate that it would be difficult to provide bacterial compliance under the highly variable effluent quality that is experienced at the plant. It is well-known that UV is an effective technology that can provide a cost effective approach to disinfection when a consistent effluent quality can be achieved. Thus the recommended design dose for UV disinfection is currently to be set at approximately 35 – 40 mJ/cm^2. If upstream process improvements could be implemented to provide effluent TSS that is consistently below 30 mg/L, then it is possible to reduce the design dose to the design dose recommended by the UV equipment manufacturer of 19 mJ/cm^2.

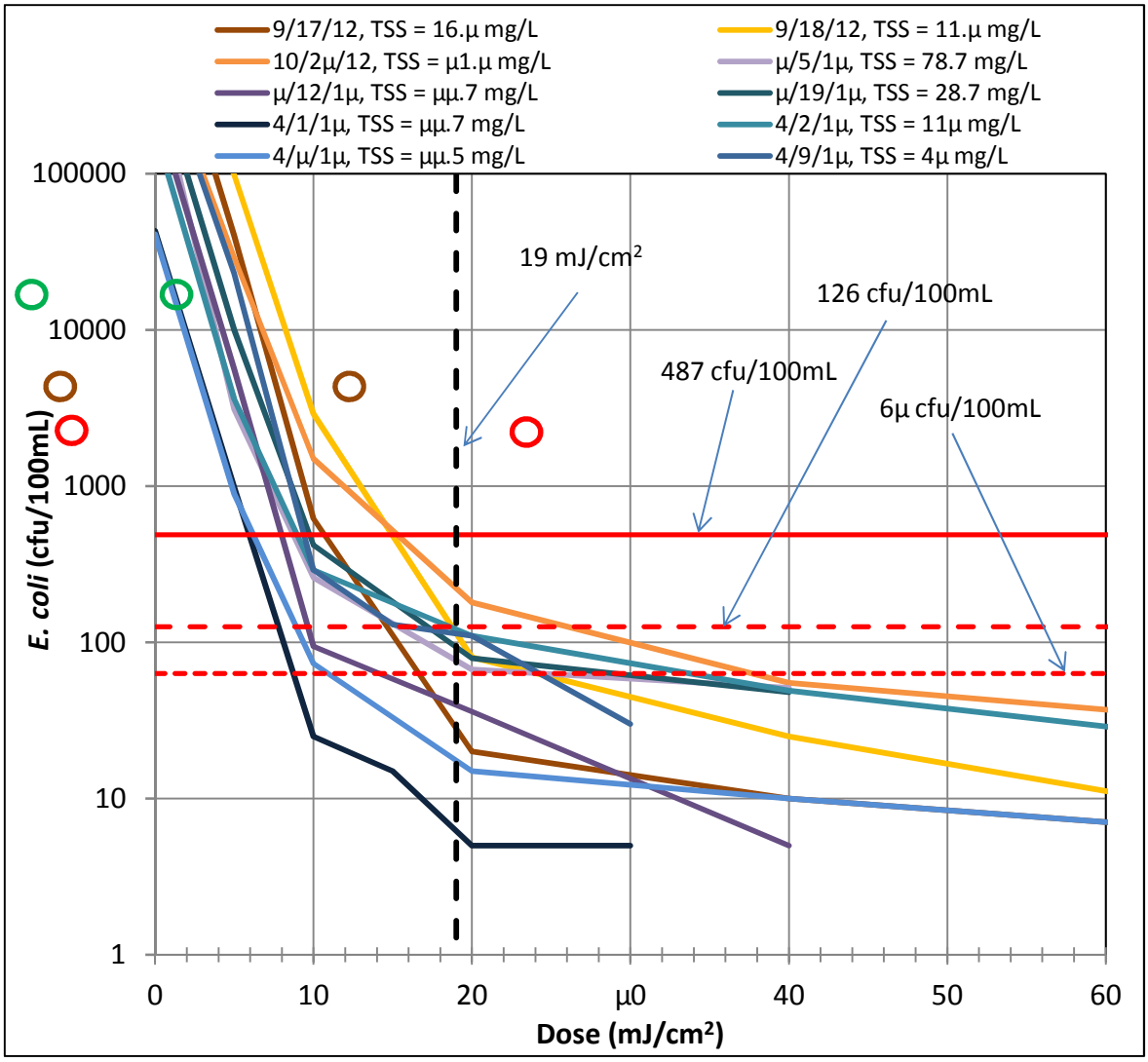


Figure µ-16 UV inactivation of *E. coli* in samples of Maxson WWTP effluent

Clearly there is a significant effect of TSS concentration on UV dose-delivery because particles can scatter UV light as well as shield bacteria within the TSS particles. This shielding effect is also a function of particle size. With respect to the actual range of particle sizes that can impact UV disinfection efficacy, the Water Environment Research Foundation (1999) indicated that 11 to 12 microns is the particle size where particle shielding starts to affect disinfection. However, the extent to which bacteria associate with particles appears to vary widely and is site specific. Factors that affect bacterial association with particles include particle size, the nature of the particles, treatment type, and sludge age. Several studies have demonstrated that the protection provided by particles increases with particle size (Ho and Bohm, 1981; Qualls et al., 1983 and 1985). These studies showed that both the dose and the level of survival at which the dose-response curve begins to tail decreases with a

decrease in the size of particles. Particles larger than 20 microns have been clearly shown to be more important in shielding than smaller particles (Qualls et al., 1983 and 1985).

As a result, it is of interest to characterize the size distribution of TSS from a given facility. The average TSS value for Maxson effluent during the pilot period was 51 mg/L, well above the historical average of 30 mg/L. Additional data was collected with respect to characterizing TSS in the samples that were collected for collimated beam testing. Data were collected using a FloCAM® particle size analyzer which is an automated particle analysis instrument that uses digital imaging for measuring size and shape of microscopic particles in a fluid medium. An example of the graphical output from the analysis is provided in **Figure 3-17**.

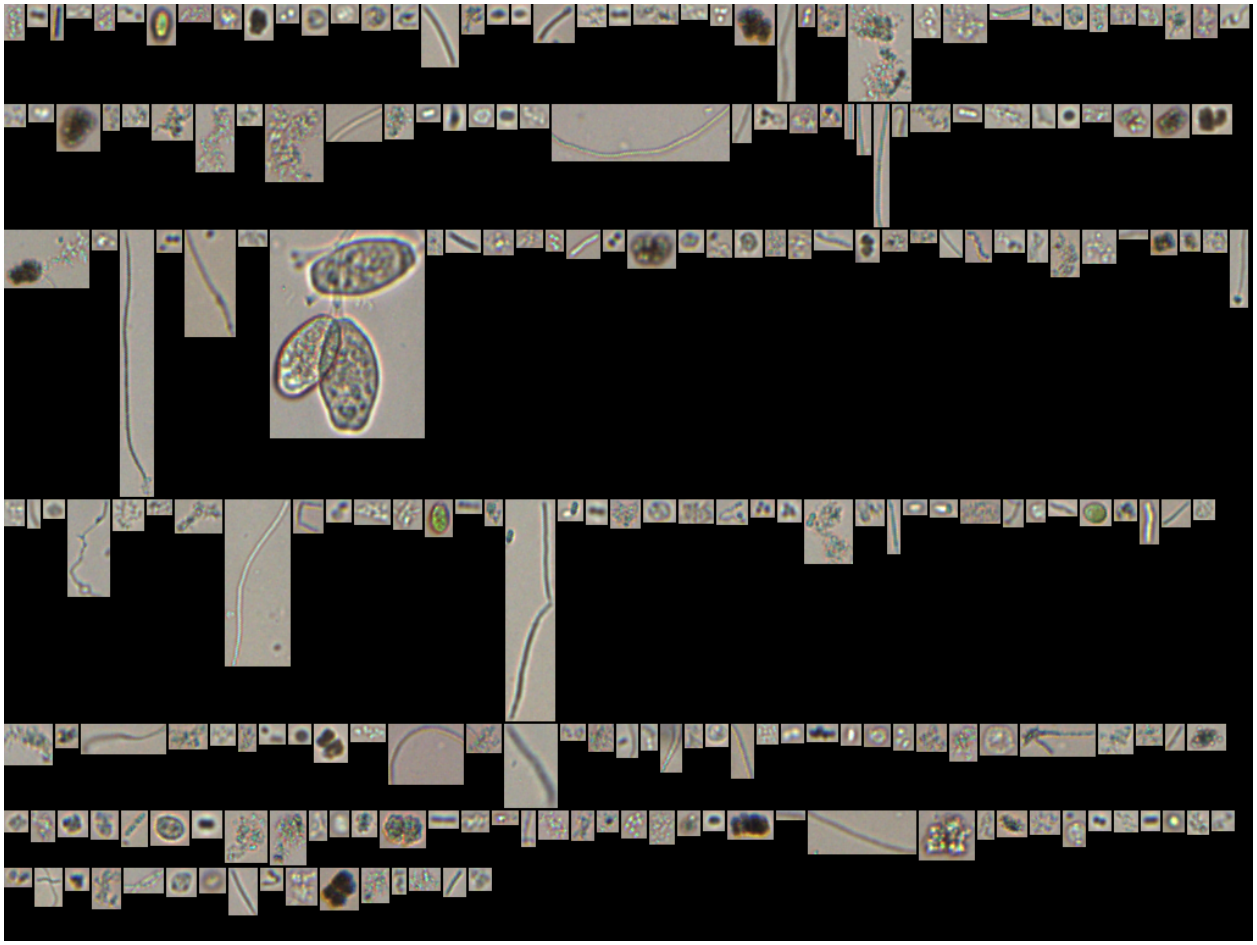


Figure µ-17 Example output from FloCAM® for samples collected from Maxson WWTP

A summary of the average particle size distributions of all TSS samples characterized during the pilot are shown in **Figure 3-18**. The information provided in **Figure 3-18** shows that about 85% of TSS particles are smaller than 20 µm which could be why better than expected performance is sometimes observed for high TSS samples. The drawback to small particles is that they may not settle well in secondary clarifiers.

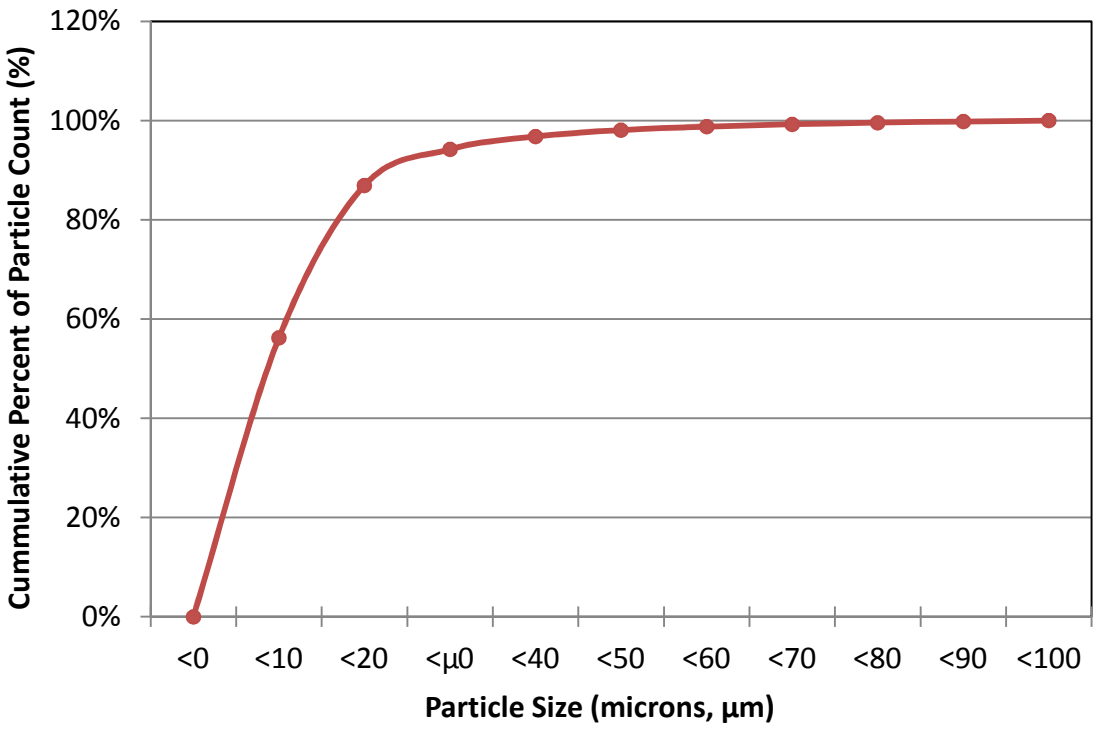


Figure µ-18 Average of all particle size distribution analyses corresponding to collimated beam tests conducted during the pilot period

µ.5.2 Validation of the Third-Party Bioassay

For wastewater disinfection, there are formally recognized protocols for verification of UV equipment for specific applications. These include procedures described in the 1986 US EPA Municipal Wastewater Disinfection Design Guidance Manual (EPA, 1986) as well as the IUVA Uniform Protocol for Wastewater UV Validation (Whitby et al., 2011) which is focused on low dose applications for secondary effluent. These protocols provide validation of the performance of specific equipment over a prescribed operating range (flow, UVT, power, etc.) as defined by the manufacturer for a specific disinfection application (e.g., reuse or secondary effluent disinfection). Only UV systems that have been bioassay validated using one of the aforementioned protocols should be considered for application at the Maxson WWTP.

At one time, UV doses were calculated based on a Point Source Summation (PSS) method, using the physical dimensions of a UV system, known UV lamp characteristics and expected UV transmittance, to calculate UV dose. The drawbacks to this approach were that the computed conditions in the UV reactor frequently did not reflect the true delivered UV dose. While numerous secondary wastewater UV disinfection systems worldwide have been successfully designed utilizing this method, there have been some capacity failures due to the "black box" design of the UV system in which the engineered safety factor is not well known. Bioassay validation of UV systems (in contrast to PSS) is based on data collected during validation testing. For bioassay validation of a UV system, surrogate organisms are used in lieu of the target organism, and hydraulic performance and real intensity distribution of the UV system are taken into account.

There are a number of different surrogate organisms that have been used for sizing UV systems. And, while MS2 has most frequently been used as a standard surrogate organism in the UV industry, there

are drawbacks to use of this for sizing equipment systems for secondary effluent applications (Salveson and Bell, 2012). The objective for selecting a bioassay organism is to most closely match the dose-response of the target organism used in compliance monitoring. For inactivation of organisms such as total or fecal coliforms, where high UV doses are not necessary to achieve discharge compliance, T1 is the preferred surrogate organism. More detailed information on validation methods to account for reduction equivalent dose bias for wastewater UV reactors is provided by Wright et al. (2009). The bioassay equation developed for the TrojanSIGNA pilot was based on T1. Information collected during piloting was used to verify this bioassay for applicability at this site. The validation equation is based on lamp power, hours of bank operation, flow rate, and UVT.

In order to validate the equipment for this application, a preliminary equipment layout was developed based on the collimated beam derived dose. The validation factor for T1 to *E. coli* is nearly unity (1) therefore the calculated T1 RED is nearly equal to the dose determined by the collimated beam testing. The proposed equipment configuration for the Maxson WWTP includes a layout with four banks in series. The number of channels will be finalized when the final design UVT is established. Thus, to interpret data collected during this evaluation, it is important to understand that the single bank in the pilot system represents only one-fourth (1/4) of the total design dose of a proposed system and the inactivation rates that are observed would represent roughly 1/4 of the design rate (e.g., ¼ * 4-log inactivation = 1-log inactivation).

To verify the applicability of the third party validation equation, inactivation data generated from the pilot test was compared to that predicted by the validation equation, using collimated beam test data. **Figure 3-19** shows comparison of measured and predicted T1 RED which were considerably closer in value than anticipated, particularly considering that only one sample had a TSS value less than 30 mg/L. That sample, collected on March 19, 2013 had a TSS of 28.7 mg/L; the difference in the measured RED was within 5-percent of the predicted value and is identified in **Figure 3-19**. The information shown in **Figure 3-19** shows, that even at TSS concentrations that extend beyond 30 mg/L, disinfection could be achieved for some samples, providing additional operational flexibility with respect to TSS. Plotted as measured versus predicted dose, a strong statistical correlation was noted as shown in **Figure 3-20**.

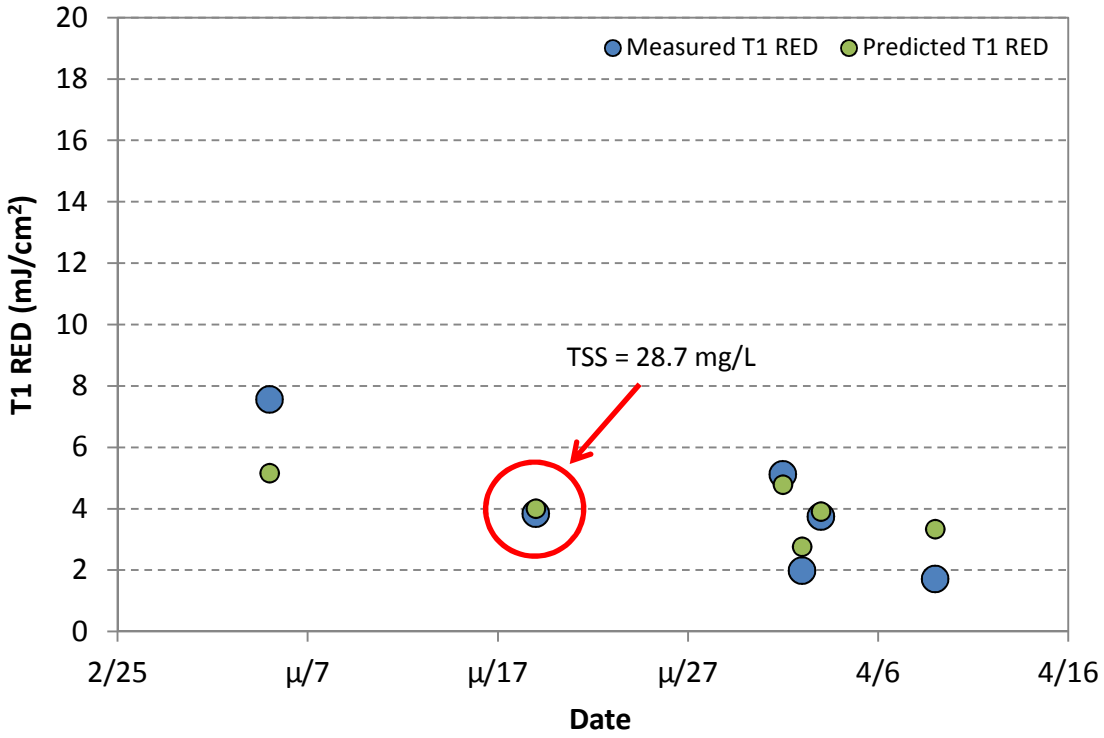


Figure µ-19 Comparison of pilot test results to results predicted by validation equation

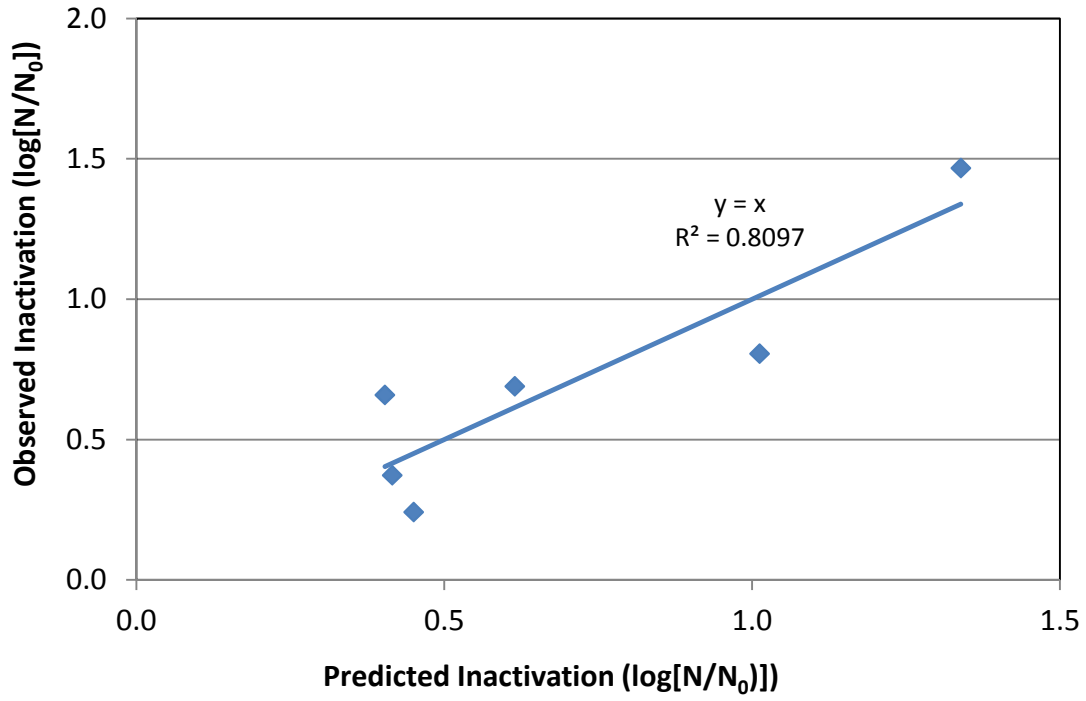


Figure µ-20 Measured versus predicted *E. coli* inactivation from collimated beam sample evaluation

In addition to the analysis conducted using collimated beam test data to confirm disinfection performance, daily *E. coli* grab samples were averaged to calculate the T1 RED. The challenge with this method is that the sample collected in the UV system influent is not the same "packet" of water that is collected at the effluent of the system, and additional variability is introduced into the calculation of dose. Nonetheless, the predicted dose calculated from the daily *E. coli* inactivation data showed good correlation with the predicted dose as shown in **Figure 3-21.** As noted previously, this is remarkable considering that a substantial fraction of samples had TSS values in excess of 30 mg/L.

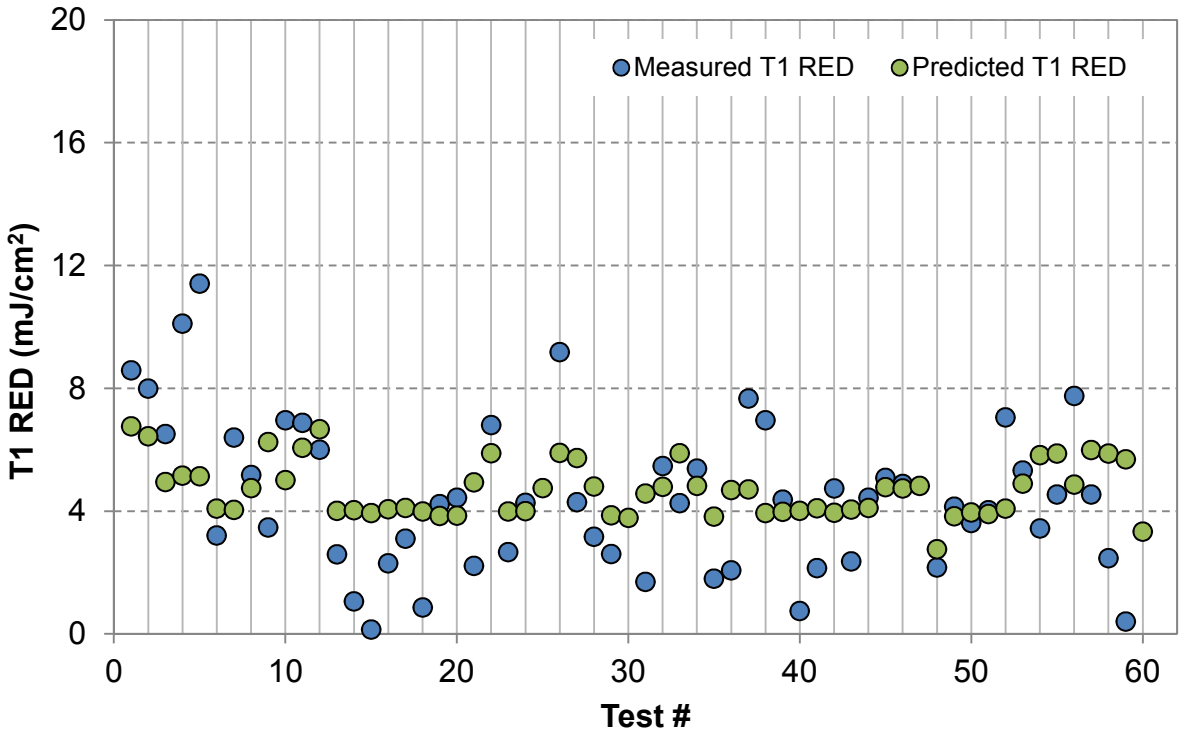


Figure µ-21 Comparison of all pilot test results to results predicted by validation equation

In summary, the UV design dose as determined by collimated beam could be set at 19 mJ/cm^2 assuming that upstream process improvements could be implemented to consistently improve effluent water quality. Until the water quality is improved consistently, UV disinfection is not a viable option at the Maxson WWTP.

µ.6 Summary of Results

As previously described, water quality has a strong impact on the design dose for any disinfection method. For sodium hypochlorite and PAA, chemical dose is impacted by chemical demand which can sometimes be predicted using online monitoring parameters such as color or UVT. However, in this evaluation there was no clear relationship allowing either UVT or color to support predicting chemical demand. As a result, for both of these processes, it is recommended to use the doses identified by evaluation of dose response and residual response relationships as described in Sections 3.2.2 and 3.3.2. The recommended residual set point for design doses for sodium hypochlorite and PAA are 20 mg/L and 13 mg/L respectively. In the case of both chemical disinfectants, because the residual concentrations that are required to meet bacterial compliance are high and in excess of the total

residual chlorine or total residual oxidant limit proposed in the permit a dechlorination or quenching system would be required.

With respect to UV disinfection, as the plant is currently configured and operated, the process is likely not feasible. However, if other process improvements are implemented at the facility that would allow consistent TSS performance below 30 mg/L, it is possible that a design dose of 19 mJ/cm^2, as a T1 RED, could be applied; however, additional collimated beam tests would be recommended upon implementation of process improvements. Further, while UVT is relatively low in the plant effluent, there are equipment systems available that are validated to 15-percent UVT; process control for this type of system would be based on an internal program that uses flow and UV intensity sensor signals which change in response to UVT. And, while issues associated with low UVT may be overcome by increasing the UV intensity (by adding more equipment), this same approach cannot be used to address treatment for effluent with TSS higher than approximately 30 mg/L.

The City of Memphis recognizes the impact of water quality on the disinfection process and the associated costs. As a result, a treatment process evaluation has been conducted to analyze potential process improvements that could improve effluent quality and process control. A copy of the process evaluation memorandum is provided in **Appendix A**. The recommendations in the process evaluation report provide a summary of process improvements that would allow the plant to consistently achieve TSS concentrations such that all three disinfection technologies are technically feasible.

Section 4
Conceptual Cost Estimates

Planning level cost estimates have been developed for implementation of chlorine, PAA and UV disinfection using the results obtained during this pilot testing as well as the process evaluation that was conducted to address effluent quality consistency. Costs developed in this preliminary analysis are based on general requirements of each system, including chemical storage requirements, energy costs and auxiliary equipment. These estimates rely on the use of previous estimates and historical data from comparable work, estimating guides, handbooks and costing curves, and are intended for planning purposes and comparing alternatives. For that reason, subtotaled and totaled costs have been rounded to two significant figures. Costs are provided in current (2013) dollars without escalation. The actual cost of any project will depend on actual labor and material costs for competitive bids, project complexity, competitive market condition, actual site conditions, final scope of work, implementation schedule, continuity of personnel and engineering.

It is important to note that in all cases, conservative assumptions regarding equipment redundancy including EPA Class I Reliability guidelines were applied to each system. With more detailed engineering information, the equipment costs and associated contingencies could be reduced. Lifecycle costs were calculated using the following assumptions: project life of 20 years, 4.13 percent interest rate, 3.00 percent inflation rate, and 2.00 percent electric escalation rate, above the base inflation rate. Maintenance labor costs were estimated at a fully loaded labor rate of $40.00 per hour.

4.1 Sodium Hypochlorite Disinfection System Cost

Sizing a hypochlorination and sodium bisulfite dechlorination system requires experimental confirmation of the residual chlorine concentration (C_R) that yields sufficient bacterial inactivation for a given contact time (T). With the design dose determined, sizing the components of a hypochlorination system is straightforward; because total residual chlorine is a permit requirement, dechlorination facilities are required. Operation of a bulk hypochlorite system is comparable to other liquid chemicals fed at treatment plants. Sodium hypochlorite solution can be added directly to the water from storage tanks with chemical feed pumps. Mixing is necessary at the point of chemical addition to optimize chemical use rates and can be accomplished with a chemical induction system with or without a mixer provided in the contact tank.

While sodium hypochlorite does not require highly specialized equipment, the sizing, design and operation of a chlorination system with liquid sodium hypochlorite is specified under the *Tennessee Design Criteria for Sewerage Works*. Chapter 10.2 provides the specific design guidance for disinfection using chlorine, in absence of site-specific data:

- *Contact chambers shall be sized to provide a minimum of 30 minutes detention at average design flow and 15 minutes detention at daily peak design flow, whichever is greater.*
- *The contact chambers should be baffled to minimize short-circuiting and back mixing of the chlorinated wastewater to such an extent that plug flow is approached.*
- *For treatment facility designs of 0.5 mgd and greater, continuously modulated dosage control systems should be used. The control system should adjust the chlorine dosage rate to accommodate*

fluctuations in effluent chlorine demand and residual caused by changes in waste flow and waste characteristics with a maximum lag time of five minutes. These facilities should also utilize continuous chlorine residual monitoring.

4.1.1 Sodium Hypochlorite System Description as Basis of Cost

At the Maxson WWTP, two of the existing clarifiers were originally constructed as chlorine contact tanks designed to provide the TDEC required detention time. While an existing structure is potentially available for renovation to its original purpose, it has been assumed that a new structure would be provided for providing the necessary contact time for disinfection. A bulk liquid hypochlorite and sodium bisulfite dechlorination system at Maxson will also require new equipment including a tank farm with bulk storage tanks and secondary containment, a chemical storage and feed building including chemical metering pumps and control, chlorine residual analyzers, injection and chemical mixing in the contact basins, and dechlorination chemical injection and mixing at the end of the basin. The required chemical storage and feed systems will include storage for 14 days of chemicals for average flows. All chemical feed pumps will be provided with the appropriate turndown and redundancy to meet EPA class I reliability guidelines.

4.1.2 Summary of Hypochlorite System Capital Costs

Cost estimates for the proposed modifications were obtained from CDM Smith's construction services group, CCI. Major equipment capital costs and construction cost estimates were developed and include new bulk hypochlorite and bisulfite chemical storage and feed equipment, electrical upgrades, instrumentation and controls, and necessary site work. Line item allowances for instrumentation and controls, electrical upgrades and other related facility modifications have been provided based on recent cost estimates from similar projects. While the exact size and layout of equipment will be determined during final design this section summarizes the assumptions used in developing cost estimates for the alternatives evaluation.

4.1.2.1 Chemical Storage Facilities and Feed Equipment

The new system includes a new chlorine contact tank to provide 15 minutes of contact time, as previously noted. Site/civil modifications will be required to provide chemical deliveries to new chemical storage facilities. Additionally, it is recommended to house chemical feed systems in a protected environment and it has been assumed that a new chemical feed building would be provided. While the geotechnical analysis has not been conducted, the chemical feed building may also require alleviation of buoyant forces since construction would potentially be in the levee zone; conservative costs have been provided to account for such construction conditions.

Chemical storage will be provided in tanks located outdoors with appropriate secondary containment; planning level costs have assumed that the storage time for sodium hypochlorite is 14 days because Memphis has ready access to chemical suppliers that can provide adequate frequency of chemical deliveries. A 30-day upper limit for storage should be not be exceeded, even if chemical use rates decrease during certain periods because sodium hypochlorite solutions are unstable and will decompose during storage. The degree of decomposition increases with the length of storage, temperature, exposure to sunlight, impurities in the solution, and decreasing pH; off-gassing can also be an issue with extended storage periods.

The chemical feed building will be constructed from durable materials that can be easily maintained and will be consistent with the architectural finishes already onsite. This design will meet the hazardous building type criteria for the type and quantity of materials to be stored and the hazardous

building type will be designed to meet the required local codes. Personnel safety equipment, emergency showers/eye washes and other necessary equipment will be provided. An automatic sprinkler system may be required for the chemical storage building and these discussions will be coordinated with the local fire marshal at 30% design to confirm if an emergency sprinkler system and any other emergency systems are required.

As the basis for developing costs, it has been assumed that the new chlorine contact tank could be located approximately south of the existing final (retrofitted) clarifiers with a new chemical feed building located in the vicinity. While the exact location of the building would be determined during final design, the size of the building would be approximately 50-ft by 50-ft in plan; it will also have an electrical room and maintenance room. The containment areas for chemical feed equipment in the building will be coated to protect the concrete against accidental chemical spills and will require a large pad size; and, the feed equipment for different chemicals will remain in separate containment areas to prevent accidental mixing of spilled chemicals.

4.1.2.2 Site Work and Hydraulic Upgrades

In order to facilitate chemical deliveries, provisions for minor site improvements have been included in this cost. In addition to providing for chemical delivery to new chemical storage facilities, which have been assumed to be an outdoor tank farm with appropriate secondary containment as noted above, yard piping and other hydraulic upgrades may be necessary to move chemicals from the storage areas to day tanks and ultimately the final feed point. The costs have included an allowance for these improvements. Effluent flow monitoring for implementation of dose pacing and residual control will be necessary for process control for any of the disinfection alternatives. However, because this cost will be similar for all three alternatives, it was not considered a differentiator in the process evaluation and has not been included in the cost estimate; the most cost-effective method of flow monitoring will be determined during detailed design.

4.1.2.µ Instrumentation and Controls

A new control system shall be put in place to monitor and control the sodium hypochlorite system which includes online instrumentation for total chlorine residual analysis. Signals from the online analyzers will be used to provide automatic control for sodium hypochlorite and sodium bisulfite feed. All Input/Output (I/O) signals from the disinfection system shall be hardwired to a PLC located at the chemical feed building. Additional coordination will be required with the plant staff to provide that the proposed system can be integrated into the existing plant process control system.

4.1.2.4 Electrical Upgrades

Electrical requirements for equipment such as analyzers and chemical feed pumps is quite low compared to other major equipment at a wastewater treatment facility and based on the experience from sizing electrically operated equipment for other chemical disinfection systems, the total connected load of the disinfection system is often a small part of the overall power draw with the majority of the connected power being required for heating/ventilating/air conditioning equipment for support structures. The chlorination and dechlorination processes require several small motors in the range of approximately 5 horsepower. The largest process motor loads are anticipated to be equipment to provide chemical induction and rapid mix. Generally, the electrical requirements for hypochlorite systems would be rated for 480-V, 3-phase or 240-V, 3-phase power, depending upon the equipment selected for installation. Instrumentation devices, such as level sensors, analyzers, samplers, receptacles, light fixtures and other miscellaneous loads will be designed to operate on a

120-V, 1-phase power source. Considering these factors, a typical electrical allowance has been provided as a percentage of the chemical facilities costs.

4.1.2.5 Summary of Capital Costs

A summary of the capital costs for the sodium hypochlorite disinfection system described here is provided in **Table 4-1** using the hypochlorite dose information obtained from the pilot testing performed in 2013.

Table 4-1 Summary of capital costs for chlorination-dechlorination system

Capital Costs for Chlorination/Dechlorination System at the Maxson WWTP Facility			
Contact Tank	LS	$	µ,600,000
Chemical Storage Facilities and Feed Equipment	LS	$	µ,µ00,000
Site Work (Hydraulic Upgrades + Rail Upgrades)	LS	$	1,500,000
Instrumentation & Controls	LS	$	µ50,000
Electrical Upgrades	LS	$	500,000
Construction Contingency	µ0%	$	1,700,000
Direct Costs Subtotal		**$**	**11,000,000**
Contractor GC Field General Conditions	10%	$	1,100,000
		$	12,100,000
Contractor GC Indirects, Overhead & Profit	10%	$	1,210,000
		$	1µ,µ00,000
Contractor Bonds and Insurance	µ.65%	$	490,000
Total Construction Cost		**$**	**1µ,800,000**
Planning, Design and Construction Services	15%	$	2,100,000
Utility Administration, Legal, Bonds & Insurance	µ%	$	410,000
Total Capital Cost		**$**	**16,000,000**

* Lump Sum

4.1.µ Operations and Maintenance Costs for Hypochlorite System

The key operations costs are related to the chemical use; however, it is also anticipated that it would take a full-time employee to monitor and maintain the system to provide consistent disinfection performance and optimize chemical use, year round. Using this information and the design doses previously described, a calculation of the annual operations costs associated with current process conditions is provided in **Table 4-2**; the sodium hypochlorite chemical dose also includes a 30-percent scale up factor for mixing and dispersion taking the recommended 20 mg/L dose to 26 mg/L for the purposes of cost estimating**.** It should also be noted, that while the equipment estimated for this alternative is expected to have a service life of approximately 20 years, there will be some replacement parts required during that service life. These costs, assuming an 8-hour per day labor allowance, are minor compared to the annual chemical costs and have not been included in this planning level evaluation.

Table 4-2 Summary of operating costs for chlorination-dechlorination system for current conditions

Annual O&M Costs for Chlorination/Dechlorination System at the Maxson WWTP Facility (Current Conditions)		
Average treated flow (mgd)	90	
Days per year of treatment	µ65	
Chlorine dose (mg/L)	26.0	
Percent solution bulk hypochlorite, % (bulk truck delivery)	12.5	
Specific density of bulk hypochlorite (lbs/gal)	9.8	
Gallons per year, as delivered	5,810,000	
Price per gallon, as delivered	$0.75	
Annual chemical costs for chlorine		$ 4,400,000
Sodium bisulfite dose (mg/L)	15	
Percent solution sodium bisulfite (%)	40	
Specific density of sodium bisulfite (lbs/gal)	11.2	
Gallons per year, as delivered	917,000	
Price per gallon, as delivered	$1.28	
Annual chemical costs for bisulfite		$ 1,200,000
Operations and Maintenance (hours/day)	8	
Fully loaded labor rate ($/hour)	$40.00	
Annual maintenance costs		$ 120,000
Lifecycle (years)	20	
Discount rate	4.1µ%	*P/A factor =*
Inflation rate	µ.00%	17.87
Annual Costs		$ 5,700,000
Present Value of Annual Costs		$ 102,000,000

If the City determines that it will provide process upgrades that would be required to support UV disinfection, the chlorine demand is anticipated to be reduced by up to half of the current conditions. Similar calculations were made for the proposed upgraded conditions and were compiled to represent the total annual operations and maintenance costs for application of chlorination-dechlorination by bulk hypochlorite and sodium bisulfite (**Table 4-3)**. The summary includes the total of estimates for chemicals and operation and maintenance staff similar to the current conditions.

Table 4-µ Summary of operating and maintenance costs for chlorination-dechlorination considering upstream process upgrades

Annual O&M Costs for Chlorination/Dechlorination at the Maxson WWTP Facility (Upgraded Conditions)			
Average treated flow (mgd)	90		
Days per year of treatment	µ65		
Chlorine dose (mg/L)	1µ		
Percent solution bulk hypochlorite, % (bulk truck delivery)	12.5		
Specific density of bulk hypochlorite (lbs/gal)	9.8		
Gallons per year, as delivered	2,910,000		
Price per gallon, as delivered	$0.75		
Annual chemical costs for chlorine		$	2,200,000
Sodium bisulfite dose (mg/L)	8		
Percent solution sodium bisulfite (%)	40		
Specific density of sodium bisulfite (lbs/gal)	11.2		
Gallons per year, as delivered	459,000		
Price per gallon, as delivered	$1.28		
Annual chemical costs for bisulfite		$	590,000
Operations and Maintenance (hours/day)	8		
Fully loaded labor rate ($/hour)	$40.00		
Annual maintenance costs		$	120,000
Lifecycle (years)	20		
Discount rate	4.1µ%	*P/A factor =*	
Inflation rate	µ.00%	17.87	
Annual Costs		$	2,900,000
Present Value of Annual Costs for Disinfection		$	52,000,000

4.2 Peracetic Acid System Costs

Sizing a peracetic acid (PAA) system is similar to sizing a hypochlorite system in that it requires experimental confirmation of the residual concentration (C) that yields sufficient bacterial inactivation for a given contact time (T). With the design dose determined, sizing the components of a peracetic system is straightforward. Total residual oxidant is a permit requirement, but quenching facilities will not be required due to the very low peracetic acid residual required to achieve inactivation. Operation of a bulk peracetic system is much simpler than other liquid chemicals fed at treatment plants because the maintenance of the analyzers and chemical feed equipment is provided as part of the chemical vendor's scope of supply. Peracetic acid solution can be added directly to the water from storage tanks with chemical feed pumps. Mixing is most desirable at the point of chemical addition and can be accomplished with a chemical induction system provided either with or without mechanical mixers.

The guidance in the *Tennessee Design Criteria for Sewerage Works*, Chapter 10.2, is directed toward hypochlorite systems and does not directly apply to the sizing, design and operation of peracetic acid systems. However, based on implementation of PAA disinfection at other facilities, and pilot testing results, contact times and contact basins that are appropriate for chlorine based disinfection are also appropriate for PAA disinfection.

4.2.1 PAA System Description as Basis of Cost

At the Maxson WWTP, as previously noted there is no functional existing contact basin and a new structure would be required to provide the required detention time. A bulk PAA system at Maxson

would require site work to provide for a chemical storage facility, including tanks for bulk storage and secondary containment. In addition, a chemical feed equipment building would be necessary to house chemical metering pumps and controls that would be provided by the chemical vendor; it has been assumed that storage tanks would be provided by the City. Similar to chlorine, chemical injection and chemical mixing equipment would be required to be installed in the contact basins along with PAA residual analyzers (also provided by the chemical supplier) that would be required for process control.

The required chemical storage and feed systems will include storage for 14 days of chemicals for average flows. All chemical feed pumps will be provided by the chemical supplier with the appropriate turndown and redundancy to meet EPA class I reliability guidelines. A cost proposal from FMC Environmental Solutions is provided in **Appendix B**. Electrical requirements for equipment such as analyzers and chemical feed pumps is quite low compared to other major equipment and given the lower chemical flow doses and flows that are required for PAA disinfection, in addition to the potential elimination of dechlorination facilities, the total connected load of the disinfection system is anticipated to be nearly half that of the chlorine disinfection system. Considering these factors, an electrical allowance has been provided as a percentage of the chemical facilities costs that were developed for a chlorination-dechlorination system. Similar to the chlorine alternative, costs for providing effluent flow monitoring have not been included in this evaluation; the costs for flow monitoring will be similar for both alternatives and the most cost-effective flow monitoring method will be determined during detailed design.

4.2.2 Summary of Peracetic Acid System Capital Costs

Cost estimates for the proposed modifications were obtained from CDM Smith's construction services group, CCI. Construction cost estimates were developed and include a new 15 minute contact tank and a new building to house new bulk peracetic acid chemical storage and feed equipment that would be provided by the PAA supplier; minor electrical upgrades required for supplying the chemical feed facilities, and necessary site work are also included in the chemical storage facilities estimate. Line item allowances for these improvements have been provided based on recent cost estimates from similar projects. It is of note that line items including site work and electrical upgrades are substantially lower for PAA than for chlorine because smaller chemical storage facilities are required for PAA and dechlorination (and oxidant reduction) is not required. A summary of capital costs for the PAA disinfection system described is provided in **Table 4-4.**

Table 4-4 Summary of capital cost for PAA disinfection system

Capital Costs for PAA Disinfection at the Maxson WWTP Facility			
Contact Tank	LS	$	µ,600,000
Chemical Storage Facilities and Feed Equipment	LS	$	2,000,000
Site Work (Hydraulic Upgrades + Rail Upgrades)	LS	$	1,500,000
Electrical Upgrades	LS	$	µ00,000
Construction Contingency	µ0%	$	1,100,000
Direct Costs Subtotal		**$**	**8,500,000**
Contractor GC Field General Conditions	10%	$	850,000
		$	9,400,000
Contractor GC Indirects, Overhead & Profit	10%	$	940,000
		$	10,µ00,000
Contractor Bonds and Insurance	µ.65%	$	µ80,000
Total Construction Cost		$	10,700,000
Planning, Design and Construction Services	15%	$	1,610,000
Utility Administration, Legal, Bonds & Insurance	µ%	$	µ20,000
Total Capital Cost		**$**	**12,600,000**

4.2.µ Operations and Maintenance Costs for PAA System

Similar to chlorination-dechlorination, the key operations costs for PAA disinfection are related to the chemical use. Proposal costs for PAA were obtained from a process solutions provider (**Appendix B**) that provides PAA inclusive of chemical storage and feed equipment as well as the calibration and maintenance of all related equipment. For this analysis, it has been assumed that labor costs associated with PAA disinfection would take up to 4 hours per day to monitor and maintain the system to provide consistent disinfection performance. The proposal cost information includes an unspecified performance guarantee (to be negotiated if PAA is selected for implementation) based on effluent TSS concentrations. The operations and maintenance costs for the current process operations are summarized in **Table 4-5.**

Table 4-5 Summary of operating and maintenance costs for PAA disinfection under current conditions

Annual O&M Costs for PAA Disinfection at the Maxson WWTP Facility (Current Conditions)		
Average treated flow (mgd)	90	
Days per year of treatment	µ65	
PAA cost ($/MG)	$25µ	
Annual chemical costs for PAA		$ 8,µ00,000
Operations and Maintenance (hours/day)	4	
Fully loaded labor rate ($/hour)	$40.00	
Annual maintenance costs		$ 60,000
Lifecycle (years)	20	
Discount rate	4.1µ%	*P/A factor =*
Inflation rate	µ.00%	17.87
Annual Costs		$ 8,400,000
Present Value of Annual Costs		$ 149,000,000

In order to compare the costs of treatment with chlorine under the assumption that upstream process upgrades would be implemented to provide improved effluent TSS, an estimate is also provided in **Table 4-6**.

Table 4-6 Summary of operating and maintenance costs for PAA considering upstream process upgrades

Annual O&M Costs for PAA Disinfection at the Maxson WWTP Facility (Upgraded Conditions)		
Average treated flow (mgd)	90	
Days per year of treatment < 15 mg/L	24µ	
Days per year of treatment 15 - µ0 mg/L	122	
PAA cost for TSS < 15 mg/L ($/MG)	$89	
PAA cost for TSS 15 - µ0 mg/L ($/MG)	$15µ	
Annual chemical costs for PAA		$ µ,600,000
Operations and Maintenance (hours/day)	4	
Fully loaded labor rate ($/hour)	$40.00	
Annual maintenance costs		$ 40,000
Lifecycle (years)	20	
Discount rate	4.1µ%	*P/A factor =*
Inflation rate	µ.00%	17.87
Annual Costs		$ µ,600,000
Present Value of Annual Costs		$ 65,000,000

4.µ UV Disinfection System Cost

The actual dose required to meet disinfection compliance depends on site-specific factors at a given WWTP. Once dose has been determined, as previously described in Section 3.5.1, the UV intensity and exposure time required to deliver the necessary dose are a function of the UV system, operating parameters and water quality. The effluent water quality affects the performance of a UV system by altering the UV intensity delivered within the reactor and, consequently, the UV dose received by the organisms in the wastewater. The most important water quality parameters are UVT and the TSS concentration and particle size as previously noted. As a result, if UV disinfection is to be a feasible process alternative at the Maxson WWTP, it will be necessary to implement process improvements that would provide effluent quality that consistently meets an upper limit of 30 mg/L of TSS, similar to most conventional secondary WWTP designs.

In order to provide an estimate of the costs associated with process upgrades to support UV disinfection, the City has requested that CDM Smith conduct a holistic evaluation of the liquid processes at the Maxson WWTP to address solids loading and clarifier performance to ensure disinfection optimization. Other process objectives related to the analysis included a discussion of concerns with odor control at the plant, particularly at the existing biotowers and potential future capacity issues at the plant. The process analysis report is provided in **Appendix A** and recommends demolition of the existing biotowers and conversion of the process to conventional activated sludge.

Even if effluent quality is ideal, delivery of the UV dose is key to ensuring compliance with the discharge permit limits. Equipment sizing and process control are essential to successful UV operation. In order to maintain system control as well as efficiency, automatic control will be used; the system will be provided with capabilities for manual override. Automated controls should only be applied over the range of water quality and operational conditions for which the system has been validated.

For wastewater disinfection, there are formally recognized protocols for verification of UV equipment for specific applications. The standard protocol used for sizing equipment for this evaluation was the IUVA Uniform Protocol for Wastewater UV Validation Applications (2011) which is focused secondary effluent applications. This protocol provides validation of the performance of specific equipment over a prescribed operating range (flow, UVT, power, etc.) as defined by the manufacturer for a specific disinfection application (e.g., reuse or secondary effluent disinfection). A UV system that has been bioassay validated using the aforementioned protocol has been considered for application at the Maxson WWTP.

In addition to selecting the appropriate equipment to deliver the design dose, there are operational considerations that must be addressed when implementing UV disinfection. Fouling of the external surfaces of the lamp sleeves and other wetted components (e.g., monitoring windows of UV sensors) of UV reactors is one of these factors. Fouling reduces the transmittance of UV light and can affect measured UV intensity and dose monitoring that is used for automatic process control. System fouling can be, and is accounted for, with a fouling/aging factor in the design of a UV system as well as provisions for automatic mechanical and chemical cleaning systems.

4.µ.1 UV System Description as Basis of Cost

For UV disinfection at the Maxson WWTP, an open channel reactor containing arrays of UV lamps would be provided. The UV system would include a power supply, an electrical system, lamps, quartz sleeves, a cleaning mechanism, as well as a mechanical system to lift the system from the channel for maintenance. Power is provided to the UV system through electronic drivers that also control UV lamps. The UV process can be controlled using flow or dose pacing, with the most efficient systems utilizing both signals. Thus, the UV control system requires a flow signal, as well as a sensor system for monitoring UVT and UV intensity. With respect to flow monitoring, it was assumed that the flow measurement would be conducted using a Parshall flume at the end of each UV channel. The reactor design will be optimized for delivery of the UV dose and hydrodynamics while providing redundancy and flexibility for variations in flow rates. As a result if, UV disinfection is selected as the preferred method of disinfection, it is recommended to conduct computational fluid dynamics modeling of the system to ensure appropriate flow split and good reactor hydraulics.

Because UV disinfection has a practical limit of application at a maximum TSS concentration of 30 mg/L, additional upstream process improvements have been included in the evaluation as described in **Appendix A**. For the purposes of developing the conceptual cost for UV at the Maxson WWTP, a comprehensive capital cost was applied that reflects the recommended process upgrades as outlined in the description of Alternative 1 which includes removal of the biotowers and upgrade of the liquid process to conventional activated sludge.

4.µ.2 Summary of UV System Costs

A cost proposal was obtained from Trojan Technologies based on the system that was piloted at the Maxson WWTP. The proposal included costs for a low-pressure, high output UV system to treat wastewater at three different UVT values, representing the range of values that are observed at the facility. Based on the UVT data previously collected at the facility and considerations for process upgrades at the facility, it is anticipated that a design UVT of 35% could be achieved. The 45 percent UVT scenario was used as the basis for cost the UV option cost estimate; the equipment required to treat effluent with a 45 percent UVT would include 5 channels (4 duty and 1 standby), with 4 banks per channel; each bank has 64 UV lamps, for a total of 1280 lamps (**Figure 4-1**).

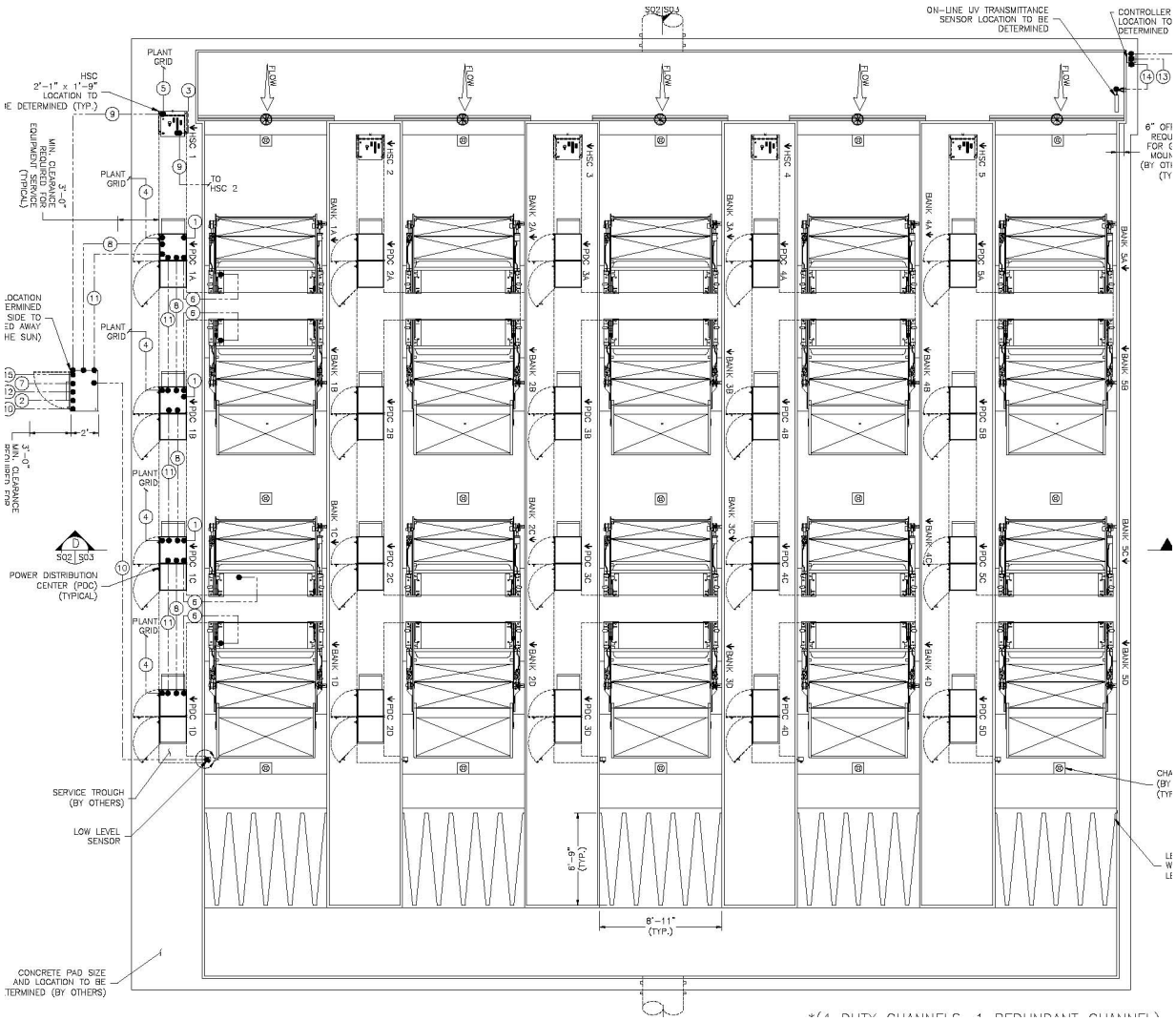


Figure 4-1 Proposed layout for UV disinfection system equipment (5 channels with 4 banks of 64 UV lamps per channel)

Cost for the UV disinfection system also includes allowances for electrical improvements, instrumentation and controls, and necessary site work and yard piping. Because disinfection is a critical process, electrical requirements for UV disinfection typically include electrical redundancy. In Tennessee, dual power feeds meet this requirement; the City already has dual power feeds to the WWTP with automatic switchgear in place. In practice, there can be power surges or interruptions associated with switchover; to protect UV equipment and provide continuous disinfection, it is recommended to include 5 minutes of uninterruptable power supply. Equipment costs, along with construction cost estimates are summarized in **Table 4-7**.

Table 4-7 Summary of capital cost for UV disinfection system

Capital Costs for UV Disinfection at the Maxson WWTP Facility			
UV Equipment	LS	$	9,µ00,000
New UV Structure and Parshall Flumes	LS	$	2,200,000
Electrical Upgrades & UPS	LS	$	1,µ00,000
Construction Contingency	µ0%	$	µ,800,000
Direct Cost Subtotal		**$**	**17,000,000**
Contractor GC Field General Conditions	10%	$	1,700,000
		$	18,700,000
Contractor GC Indirects, Overhead & Profit	10%	$	1,900,000
		$	21,000,000
Contractor Bonds and Insurance	µ.65%	$	800,000
Total Construction Cost		$	21,800,000
Planning and Engineering Design	15%	$	µ,µ00,000
Utility Administration, Legal, Bonds & Insurance	µ%	$	650,000
Total Capital Cost		**$**	**26,000,000**
Capital Cost Process Upgrades		**$**	**7µ,000,000**

Note: Provided capital costs for process upgrades represent the average cost of the conventional activated sludge and step-feed option for Alternative 1 of the Maxson WWTP Process Alternatives Evaluation (**Appendix A**).

4.µ.µ Operations and Maintenance Costs for UV System

Annual maintenance labor costs were estimated at 4 hours per day. Annual replacement costs for lamps and ballast are also estimated based on the guaranteed life of these items for year-round operation of the system at average flow. A summary of the annual operations and maintenance costs for the UV disinfection system to provide treatment of effluent from an upgraded liquid treatment process is provided in **Table 4-8**.

Table 4-8 Summary of operating and maintenance costs for UV disinfection

Annual O&M Costs for UV Disinfection Maxson WWTP Facility		
Average treated flow (mgd)	90	
Number of Lamps per MGD	6.4	
Days per year of treatment	µ65	
UV dose (mJ/cm2) as T1	19	
Number of lamps at average flow	576	
Power input per lamp (watts)	1000	
Annual Electric Usage (kW-hr/yr)	5,000,000	
Electricity cost ($/kW-hr)	$0.076	
Annual electricity costs for UV		$ µ80,000
Guaranteed lamp life (hours)	15,000	
Lamp replacement cost	$675	
Guaranteed ballast life (years)	10	
Ballast replacement cost	$990	
Annual costs for lamp replacement		$ 2µ0,000
Annual costs for ballast replacement		$ 57,000
Maintenance, hours/day	4	
Fully loaded labor rate, $/hour	$40.00	
Annual maintenance costs		$ 58,000
Lifecycle in years	20	
Discount rate	4.1µ%	*P/A factor =*
Inflation rate	µ.00%	17.87
Power escalation rate	2.00%	P/A_g 21.85
Annual Costs		$ 7µ0,000
Present Value of Annual Costs		$ 14,000,000

4.4 Lifecycle Costs Analysis

Because there are different cost impacts, capital versus operating costs, with respect to the different disinfection technologies, conducting lifecycle analysis is a necessary step in evaluating process alternatives. In order to simplify the analysis for the purposes of decision-making, the operation costs of the liquid process upgrades have been disregarded. It is important to note, if the upstream liquid processes are not upgraded as described in **Appendix A**, then UV disinfection is not a feasible option. While the process upgrades are a significant capital cost, there are additional benefits that are achieved by implementation of these improvements including addressing odor control issues and long-term capacity needs. This may need to be revisited as the City reviews the potential for implementation of the liquid process upgrade alternatives as described in **Appendix A**.

For this analysis, the capital costs and general conditions costs have been summarized along with annual operations and maintenance cost estimates. Capital costs for PAA and chlorine alternatives include installation of a contact tank to provide 15 minutes of contact time. The net present value (NPV) of the annual costs were calculated assuming a project life of 20 years, 4.13 percent interest rate and a 3.00 percent inflation rate for all disinfection alternatives. Summing the total capital costs (including general conditions and services) and the NPV of annual costs provides a comparative

lifecycle cost to aid in selection of the preferred disinfection alternative. A summary of costs for all three disinfection alternatives, including the scenarios where liquid process upgrades could be implemented to improve effluent quality, are provided in **Table 4-9**; costs are also represented graphically in **Figure 4-2.**

Table 4-9 Lifecycle analysis for disinfection alternatives under current conditions and conditions assuming liquid process upgrades

Cost Parameter	Hypochlorite	Hypochlorite Optimized	Peracetic Acid	Peracetic Acid Optimized	UV Optimized
Equipment and Facility Upgrades	$11,000,000	$84,000,000	$8,500,000	$81,500,000	$90,000,000
General Conditions and Services	$5,000,000	$5,000,000	$4,100,000	$4,100,000	$9,000,000
Total Capital Costs	**$11,000,000**	**$89,000,000**	**$12,600,000**	**$85,600,000**	**$99,000,000**
Annual O&M	$5,700,000	$2,900,000	$8,400,000	$µ,600,000	$7µ0,000
20-Year NPV of O&M	$102,000,000	$52,000,000	$149,000,000	$65,000,000	$14,000,000
Total 20-Year NPV	**$118,000,000**	**$141,000,000**	**$162,000,000**	**$151,000,000**	**$11µ,000,000**

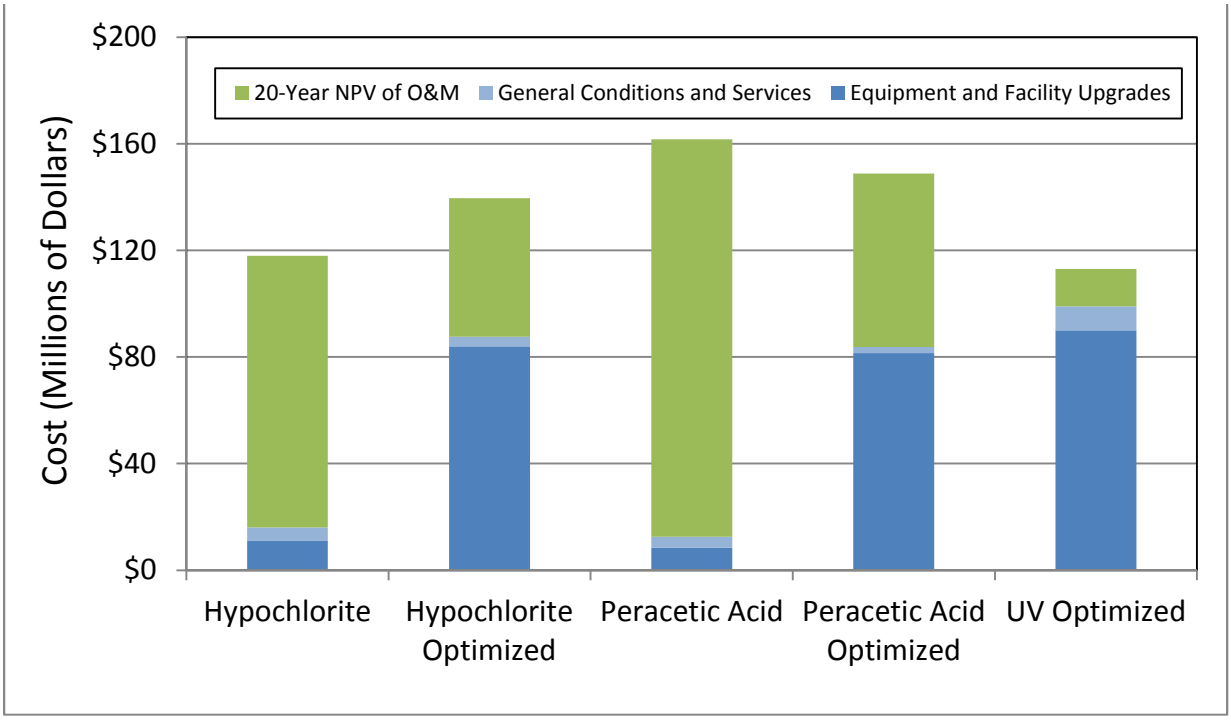


Figure 4-2 Lifecycle costs for disinfection alternatives

Section 5

Supplemental Testing & Evaluation

Since the completion of the previous pilot work, performed by CDM Smith in 2013, two major changes have occurred at the Maxson WWTP. First, during the 2013 pilot testing, a portion of the plant treatment process was being bypassed to allow for the construction/installation of the new fine screen facility prior to the primary clarifiers. Second, a major industrial contributor (Cargill) to the Maxson WWTP closed and was anticipated to result in a significant reduction in overall plant loading. As a result, supplemental pilot testing of peracetic acid (PAA) and supplemental UV related analysis were performed, as was bench testing of UV and PAA as a combined disinfectant. The supplemental testing and final disinfection alternative evaluation based upon the results of the testing are presented in the *Maxson WWTP Supplemental Pilot & Bench Disinfection Testing Report* found in **Appendix C**, and are summarized in this section.

5.1 Supplemental Pilot and Bench Testing Objectives

The purpose of the additional testing was to gather data to supplement the bench and pilot testing previously conducted at the Maxson WWTP. In order to confirm the results of previous testing, in light of the recent changes at the facility, the following objectives were addressed with respect to meeting limits for *Escherichia coli* (*E. coli*) as outlined in the current draft National Pollutant Discharge Elimination System (NPDES) permit:

- Refine the design criteria for PAA disinfection to meet disinfection limits
  - Determine the kinetic model parameters to predict PAA disinfection efficacy across a range of doses and contact times
  - Determine the design dose for average conditions to support calculation of associated operating costs
- Confirm the UV disinfection design dose to support estimates of capital and operating costs

The key objectives of the bench scale UV/PAA disinfection study included:

- Quantify and compare disinfection kinetics among several UV and PAA combinations including:
  - PAA alone, UV alone, UV followed by PAA, PAA followed by UV, simultaneous disinfection with UV and PAA.
- Propose a mechanistic model to describe the efficacy of the combined disinfectant

5.2 Supplemental Pilot and Bench Testing Results & Analysis

5.2.1 Supplemental PAA Pilot Test Results & Analysis

The PAA pilot testing commenced on Monday, May 4th, and continued through Friday, June 5th, 2015; samples were collected and submitted to Environmental Testing and Consulting Laboratory, located in Memphis, Tennessee. Sample collection and analytical methods were similar to those done in the

original PAA pilot performed in 2013. Complete results and analysis of data are provided in **Appendix C**, however a summary of the supplemental PAA pilot testing data analysis is included here.

CDM Smith worked to develop a disinfection kinetics model that best represent all the PAA pilot testing data. Standard methods for describing PAA disinfection efficacy are still being developed because the application of PAA as a wastewater disinfectant is relatively recent. CDM Smith has historically applied the Hom's model to disinfection datasets, as described above in Section 3.3. Although the correlation between the model and the measured data is 81%, there does appear to be some over-prediction at low inactivation and under predication at high inactivation. Because of the spread between the model and the measured data that was observed in the application of Hom's model, the standard concentration * time (CT) model was also applied to determine if a better fit could be found for the data. The correlation between the standard CT model was slightly stronger (84%), and displays less over and under prediction, than the Hom's model. However, there is still observable spread between the model and the measured data. A final predictive model, the Double Exponential Decay model, was applied to determine if a stronger correlation could be found. This model also utilizes the integral CT method, but uses a more complex correlation between CT and log inactivation. In this model, the bacterial population was divided into two parts, an easy to inactive portion which represents free floating bacteria, and a hard to inactivate portion, which represents particle associated bacteria. The resulting correlation is shown in **Figure 5-1**. The data is best correlated to this model (90%), and the spread between the data and the model is reduced. The PAA dosing recommendations were generated from this model.

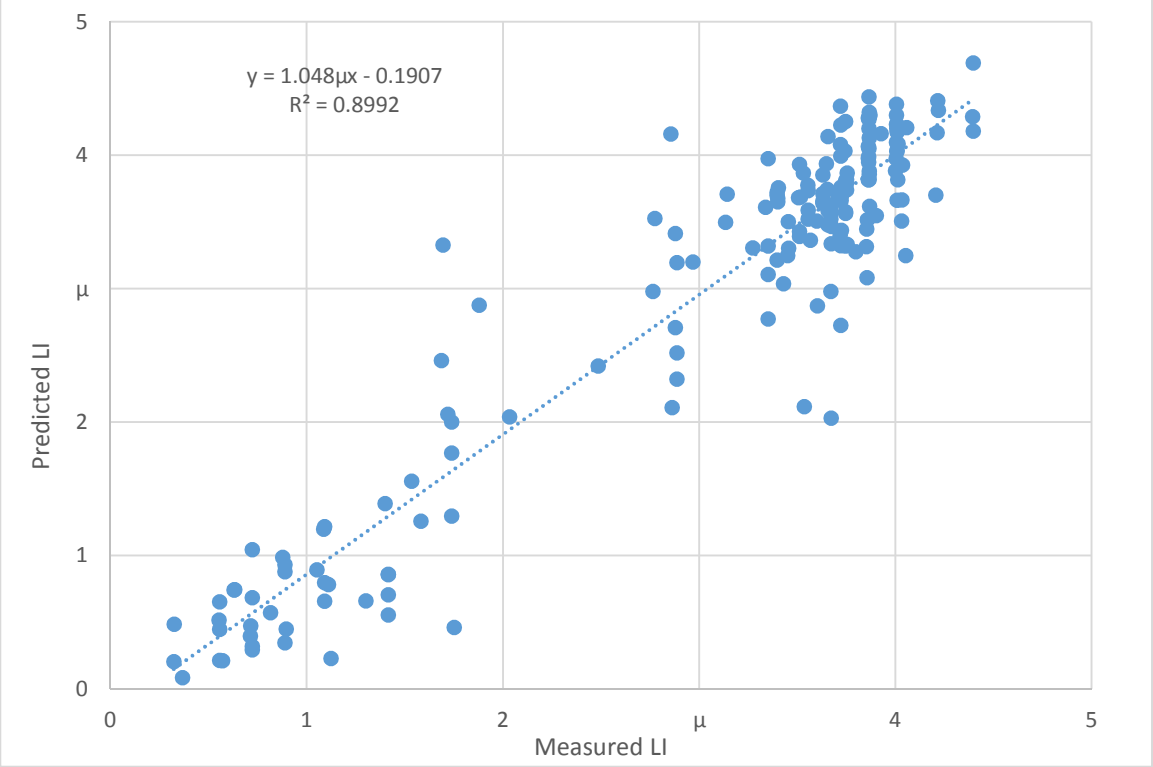


Figure 5-1 Correlation between Measured Log Inactivation and Double Exponential Decay Model Predicted Inactivation

Three disinfection design criteria were established to reflect average, peak, and minimum conditions at the WWTP. The basis for the design criteria are described in Section 4, of **Appendix C**. The model predicted CT values for these design criteria are summarized in **Table 5-1**. For conservatism, a safety factor of 1.3 is applied to the CT values to help account for scale up between the pilot and full scale application. This is shown in the CT* column.

The required CT can be achieved through numerous combination of time and PAA dose.

Table 5-1: Required PAA CTs and Design Points

Flow Conditions	Flow (MGD)	Required Log Inactivation	CT*
Permitted Average	90	µ.92	87.1
Peak Hour	170	µ.82	74.1
Daily Minimum	50	2.81	22.4

*CT results include a 1.µx safety factor for scaling up to full scale

It is worth noting that as part of the supplemental pilot and bench testing a review of the required log inactivation for the disinfection system was performed. The required log inactivation was determined based on review of a combined dataset including data measured during the supplemental PAA pilot study, data measured during the collimated beam analyses, and data from daily plant operations between 2010 and 2013. **Table 5-2** summarized the relevant statistic from this expanded dataset, and compares it against that shown in **Table 1-1**. The datasets are identical, with the exception being the average values are slightly different. The combined dataset, referred to going forward as the "dataset," was utilized for determining the revised log inactivation.

Table 5-2: Relevant Influent *E. coli* Statistics

Statistic	Updated Values	Table 1-1 Values
Maximum	5.7×10^6	5.7×10^6
Average	7.3×10^5	7.4×10^5
Minimum	1.3×10^4	1.3×10^4
Geometric Mean	5.2×10^5	5.2×10^5
10 Percentile	1.5×10^5	--
20 Percentile	2.4×10^5	--
30 Percentile	3.3×10^5	--
40 Percentile	4.6×10^5	--
50 Percentile	5.6×10^5	--
60 Percentile	7.3×10^5	--
70 Percentile	9.3×10^5	--
80 Percentile	1.3×10^6	--
90 Percentile	1.6×10^6	--
99 Percentile	--	2.0×10^6

For peak conditions, bacterial concentrations will be reduced from the 90th percentile from the dataset to one half of the daily permit limit of 487 cfu/100 mL, which is 244 cfu/100 mL. This is equal to a log inactivation of 3.82. For average conditions, the bacterial concentrations will be reduced from the

geometric mean from the dataset to one half of the monthly permit limit of 126 cfu/100 mL, which is 63 cfu/100 mL. This is equal to a log inactivation of 3.92. This is slightly different from what was presented in Section 1.4.1, as those log inactivation calculations utilized the average from that dataset, rather than the geomean, which is done here for the revised log inactivation calculation. The reason for this adjustment is because the monthly permit limit is a 30 day geomean value, therefore the value from the dataset should also be a geomean not an average. For minimum conditions, bacterial concentrations will be reduced from the 10th percentile from the dataset to one half of the daily permit limit of 487 cfu/100 mL. This is equal to a log inactivation of 2.81.

Minimum Daily Inactivation Rate Required:	$\log(1.5 \times 10^5) - \log(2.44 \times 10^2) = 2.81$
Average Monthly Inactivation Rate Required:	$\log(5.2 \times 10^5) - \log(6.\mu \times 10^1) = \mu.92$
Maximum Daily Inactivation Rate Required:	$\log(1.6 \times 10^6) - \log(2.44 \times 10^2) = \mu.82$

The difference between the original log inactivation (4.1) and the revised log inactivation of 3.92 is small.

In order to size the PAA system, a cost optimization was performed to determine the most effective combination of contact time and dose to reduce overall lifecycle costs. This was accomplished by limiting the capital cost of the contact tank to less than $10 million, and increasing the PAA contact tank (CT) size to ensure that the resulting residual PAA concentration were between 0.4 mg/L and 1.5 mg/L at the end of the CT. Based on these design criteria, a sodium bisulfite system is not required.

5.2.2 Supplemental UV Collimated Beam Results & Analysis

Several new collimated beam (CB) analyses were performed during the supplemental PAA pilot testing to determine if disinfection requirements have changed due to changes in plant influent since 2013. A comparison of the recent and historical CB data performed by Trojan Technologies is shown in **Figure 5-2**. These represent the average of the entire dataset from each year. There is no significant difference between the two datasets. The effectiveness of a UV disinfection system relies heavily on the UV transmittance (UVT) of the influent to the system. During the pilot period, the observed UVT was 16%. As discussed previously, it is anticipated that upgrades to the secondary treatment process would result in an improvement to the effluent UVT. However the industrial users have an impact on the UVT of the influent at the Maxson WWTP, which is more impacted by both color and TSS. The exact effluent UVT improvement from the upgraded treatment process cannot be quantified at this point, however it is assumed that it would be around 20%. As a result a UVT of 20% was utilized to develop the revised capital costs.

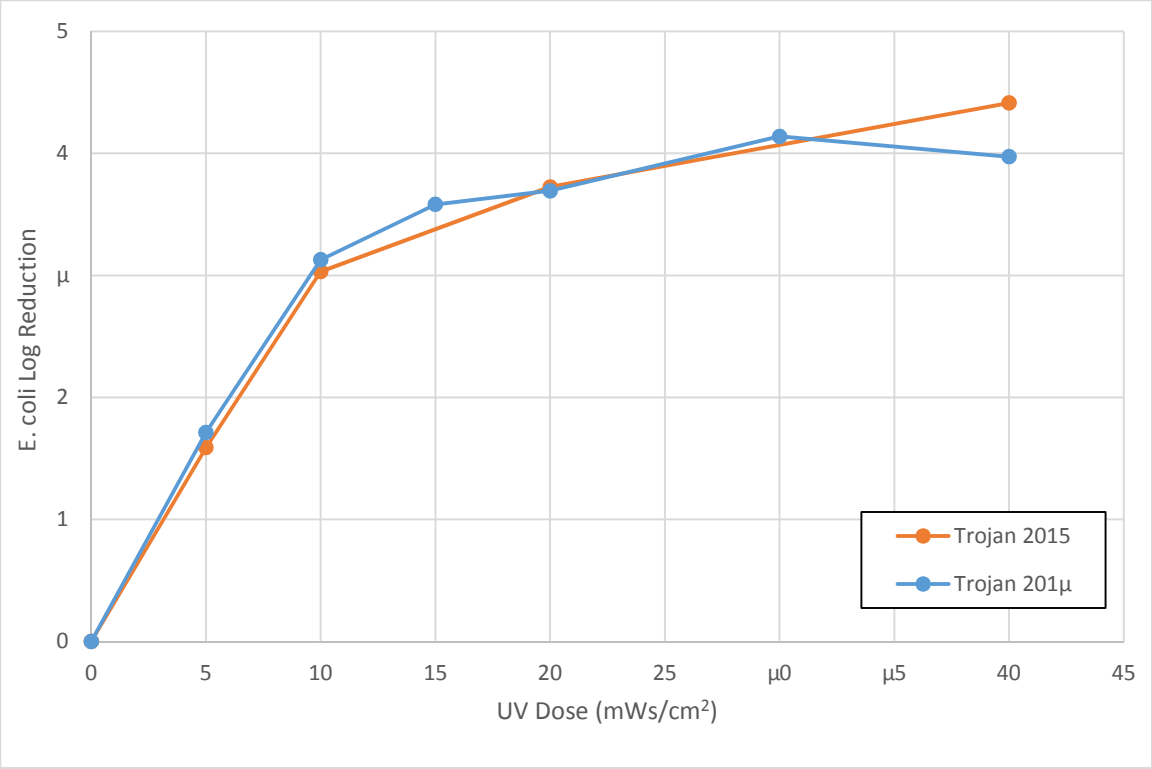


Figure 5-2: Comparison of Recent and Historical Collimated Beam Data

5.2.µ UV/PAA Test Results & Analysis

In order to investigate the feasibility and economics of implementing a combined disinfection technology strategy, bench testing was conducted to inform process selection and sizing. UV/PAA bench testing was conducted at the Maxson WWTP the week of September 21, 2015. Samples of secondary effluent were collected twice daily and were treated at bench-scale, on site. In this study, secondary effluent samples were treated with various combinations of UV doses, between 2.5 – 40 mJ/cm^2, and PAA CTs, between 2.5 – 50 mg·L^{-1}·min. To evaluate different operational scenarios the following five combinations were applied: PAA alone, UV alone, PAA followed by UV, UV followed by PAA, and simultaneous UV and PAA.

A mechanistic model was developed, based upon the results of the combined UV/PAA disinfection bench test, to predict the results of combined disinfection using UV and PAA. Results indicated that the most effective combination of the two is UV followed by PAA. **Figure 5-3** was developed to illustrate the different combinations of UV and PAA that would be required to maintain an effluent concentration of 126 cfu/100 mL of *E. coli.* Although the results are promising, further research is required to accurately describe the effect of combined disinfection, and the economic analysis that was performed based on the results did not indicate significant economic savings through application of a combined disinfection system. The full UV/PAA bench testing report is included in **Appendix C**.

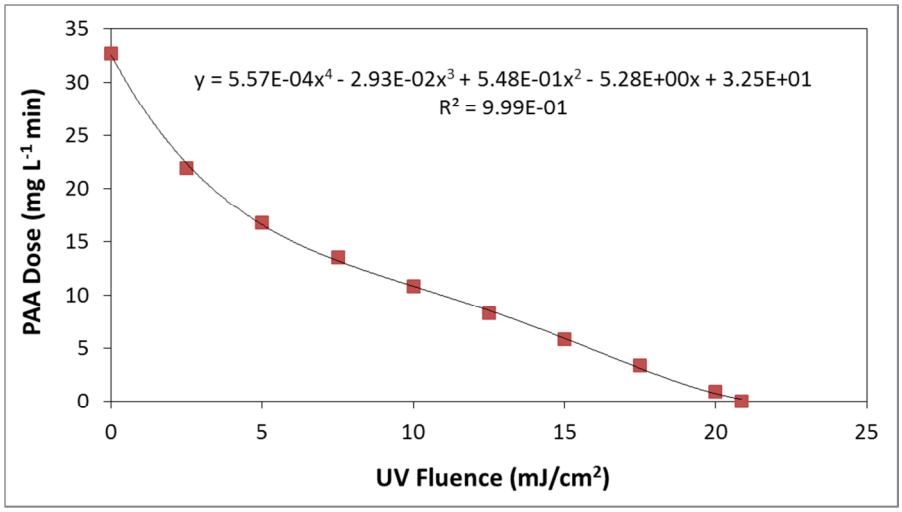
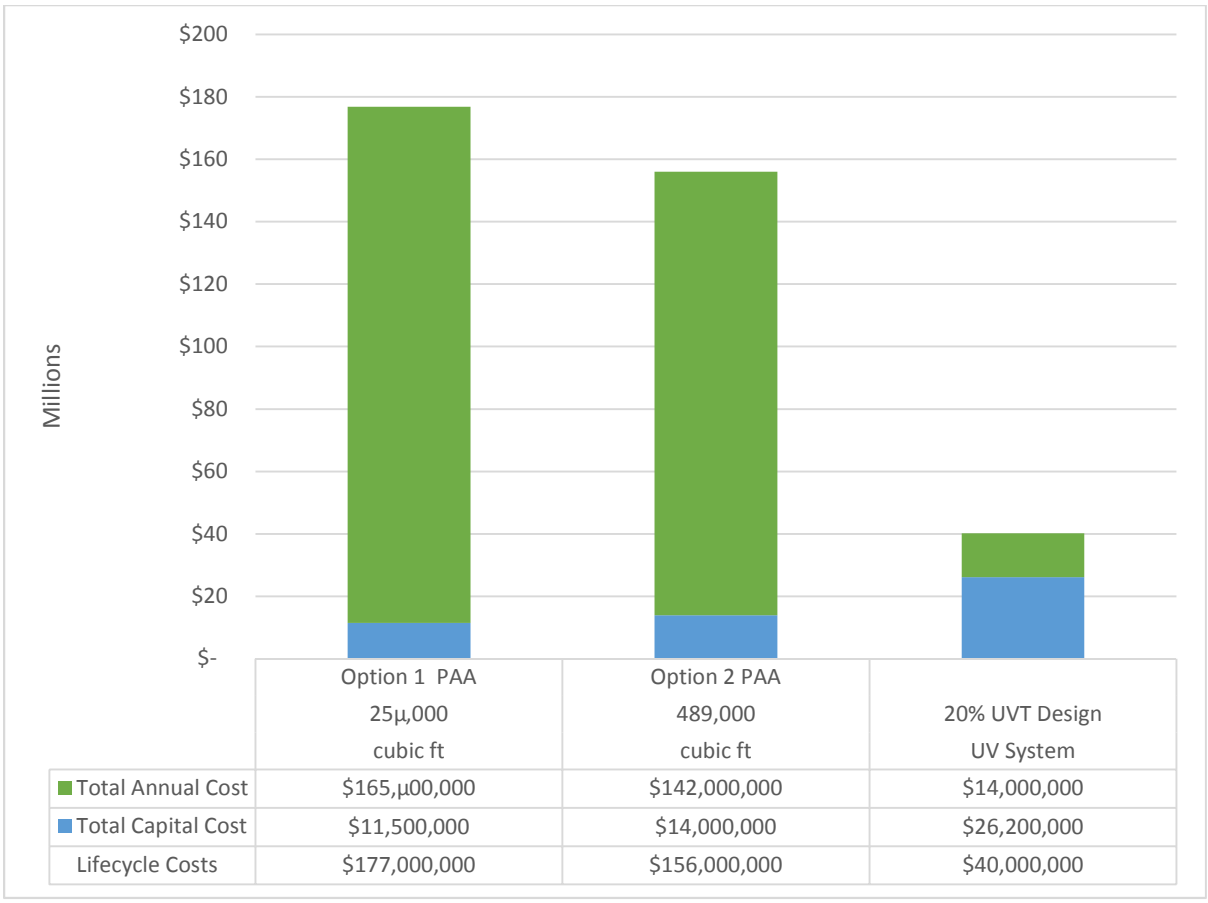


Figure 5-µ: Model predicted combinations of PAA dose and UV fluence required to achieve a E. coli disinfection target of 126 cfu / 100 mL when applying the sequential UV→PAA treatment process.

5.µ Revised Conceptual Cost Estimates

Based upon the supplemental testing performed in 2015, the conceptual costs for UV and PAA were revised. Comparative 20 year lifecycle costs for three alternative disinfection systems are illustrated in **Figure 5-4**. The first alternative is a PAA system with a contact tank providing 31 minutes of contact time at average flow, the second is a PAA system providing 31 minutes of contact team at peak flow, and the third is a UV system designed to treat effluent with a 20% UVT.



	Option 1 PAA 25µ,000 cubic ft	Option 2 PAA 489,000 cubic ft	20% UVT Design UV System
Total Annual Cost	$165,µ00,000	$142,000,000	$14,000,000
Total Capital Cost	$11,500,000	$14,000,000	$26,200,000
Lifecycle Costs	$177,000,000	$156,000,000	$40,000,000

Figure 5-4 20 Year Lifecycle Analysis of Three Disinfection Options

Providing more contact time at average flow for the PAA system eliminated the need for quenching with sodium bisulfite, although the capital costs for a small sodium bisulfite was included for emergency use. Although the lifecycle costs of the UV alternative is lower than that of the two PAA alternatives, the City of Memphis and CDM Smith discussed the impacts caused by the variability of the low UV transmittance seen in the Maxson WWTP effluent. The variability likely stems from the change in processes and raw materials utilized by industrial users within the City's collection system. Based upon these discussions it was decided to eliminate UV from the list of disinfection alternatives. Results of the detailed cost analysis and the supplemental pilot data indicate that the most cost effective contact tank size to reduce overall lifecycle cost is 489,000 cubic ft. As a result, the most cost effective disinfection alternative is PAA - Option 2.

Section 6
Recommendations

Based on a review of the analysis presented in this report, CDM Smith recommends disinfection with PAA at the Maxson WWTP. While testing conducted in support of this evaluation has demonstrated that both sodium hypochlorite and UV disinfection were also effective for achieving bacterial inactivation to meet permit compliance for *E. coli* at the Maxson WWTP; there are concerns regarding the use of chlorine disinfection, and there are uncertainties associated with low UVT effluent and further degradation of the effluent UVT. Implementation of PAA disinfection requires additional upstream process upgrades and considerations should be evaluated regarding the additional operations costs associated with these liquid process upgrades during final design.

Chlorine disinfection has the same life cycle cost as UV disinfection and is lower than PAA disinfection, however the use of a chlorination disinfection system has additional permitting requirements that include additional testing under Section 3.6.1 of the permit, as follows, making the technology more challenging to implement: ***"3.6.1 Additional Permittee Submittals (If Chlorination Disinfection System Selected).***

> *Permittee must provide the division with the types/amounts of specific chlorinated byproducts species to be in the Outfall 001 treated effluent and how newly generated byproducts are related to TRC according to the compliance schedule…"*

If the City opts to implement PAA disinfection and the associated secondary treatment process upgrades to address chemical oxidant demands in the effluent there are significant ancillary benefits to this decision. While PAA disinfection has the highest lifecycle cost, the low capital cost of the PAA disinfection system combined with the avoidance of additional permitting requirements as described above, has resulted in PAA disinfection being the selected disinfection alternative for the Maxson WWTP. Additionally, proceeding in this direction may enable the City to address other major concerns regarding odor control and future capacity issues at the Maxson WWTP.

Section 7
References

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Technical Memorandum

To: *Paul Patterson*
Scott Morgan, PE
Mike Brower

From: *CDM Smith Inc.*

Date: *November 27, 2013*

Subject: *T.E. Maxson WWTP Process Alternatives Evaluation*

1.0 Introduction

The T.E. Maxson WWTP (Maxson WWTP) is located in the southwest portion of Memphis, Tennessee at 2685 Steam Plant Road. The WWTP currently treats an average of 70 million gallons per day (mgd) of wastewater, serving the City of Memphis (City) since its commissioning in 1975. With upgrades over the years, the current liquid treatment process consists of coarse bar screens, grit removal, recently installed fine bar screens, primary clarification, high-rate biotowers, activated sludge and secondary clarification.

The City is currently planning an upgrade to provide disinfection as the final treatment process to meet requirements in the current draft National Pollution Discharge Elimination System (NPDES) permit. The process that will ultimately be selected to provide disinfection is directly impacted by the secondary effluent quality. In addition to the need to address effluent quality to minimize the costs of the new disinfection process, the facility is experiencing an increase in wastewater flows and loads, which has prompted the City to evaluate the existing plant and operations to determine what would be required to meet the original design flow of 90 mgd. As a result, the City has requested that CDM Smith conduct a holistic evaluation of the liquid processes at the Maxson WWTP to address the following objectives:

- Solids loading and clarifier performance to ensure disinfection optimization;
- Discuss concerns with odor control at the plant, particularly at the existing biotowers; and
- Potential future capacity issues at the plant.

This technical memorandum provides a summary of the process evaluation and includes an analysis of the biological treatment processes, consideration of solids loading, clarifier performance, biotower process performance, and capacity related issues. Additional evaluation of

biosolids handling, which was not identified in this scope of work, may be necessary depending upon the improvements selected for further consideration.

2.0 Evaluation Approach

Historical plant data were obtained from the City and analyzed to develop a basis of evaluation of the plant. Peaking factors for the average-day (AD), average-day maximum-month (ADMM) and maximum-day (MD) loading conditions were determined based on this analysis. These peaking factors were applied to the plant's permitted average day flow of 90 mgd as a basis for evaluating the liquid treatment processes; the design flows and loads are summarized in **Table 2-1**.

Table 2-1 Influent Design Conditions

Influent Parameters	AD	ADMM	MD
Flow (mgd)	90	126	153
BOD5 (ppd)	515,700	562,100	727,100
TSS (ppd)	426,300	550,000	703,500
TKN (ppd)	75,100	90,100	112,600
TP (ppd)	15,000	18,000	22,500
Minimum monthly Water Temp (deg C)	14	14	14

Table 2-2 provides a summary of the current draft NPDES requirements at the permitted average design flow of 90 mgd. In addition to permit compliance, this evaluation also considers the need to consistently achieve effluent total suspended solids (TSS) of less than30 milligrams per liter (mg/L). This is lower than the concentration required for discharge, according to the NPDES permit, but is a requirement for ultraviolet (UV) disinfection to be a feasible disinfection alternative. There are potential impacts on the solids handling processes as a result of the lower TSS objective, which will require further evaluation, based on the modifications selected for the liquid process.

Table 2-2 Effluent NPDES Requirements

Effluent Parameter	Maximum Daily	Average Monthly
BOD5 (mg/L)	84 (40% removal)	42 (85% removal)
TSS (mg/L)	96 (40% removal)	48 (85% removal)

There is currently no ammonia-nitrogen limit in the NPDES permit, and a total nitrogen limit is not anticipated in the foreseeable future; therefore, nitrification has not been included in the liquid treatment process evaluation. However, the alternatives have been developed such that, if

nitrification is required in a future effluent limit, the process improvements could be incorporated into any potential upgrades that would be required to achieve nitrification. While any of the alternatives developed could be later upgraded to achieve nitrification, each alternative has a different site footprint. Generally to achieve nitrification, the biomass maintained under aerobic conditions would need to be increased by approximately four times over that identified in this evaluation, which results in the need for additional aeration tankage and/or clarifiers.

While the current permit does not include nitrification or nutrient removal as requirements, there is the potential that nutrient limits will be implemented in some future permit cycle. The driver is implementation of State-developed nutrient reduction strategies, which are a major focus of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Task Force) responsible for the national strategy to reduce, mitigate, and control hypoxia in the Northern Gulf of Mexico and improve water quality in the Mississippi River Basin. The Task Force was established in 1997 and consists of 5 federal agencies and 10 state agencies.

The Task Force objectives include having each state develop and implement its own nutrient reduction strategy, which provides flexibility for tailoring the strategy's approach and components. At the same time, the Task Force recognizes that all state strategies need to include certain essential components to achieve overall goals. The participating states include Arkansas, Indiana, Illinois, Iowa, Louisiana, Kentucky, Minnesota, Mississippi, Missouri, Ohio, Tennessee and Wisconsin. Most of these states have already completed their strategies, while Arkansas, Kentucky and Tennessee continue to work on completing the final documents.

While Tennessee has yet to publish this guidance, several other discharge permits in the state reference the approach to how the state will implement its nutrient strategy. The Tennessee Department of Environment and Conservation (TDEC) has been developing its strategy to reflect the goals of EPA's March 16, 2011, *Memorandum: Working in Partnership with States to Address Phosphorus and Nitrogen Pollution through Use of a Framework for State Nutrient Reductions*. The Tennessee approach uses regional USGS SPARROW models to determine the required performance level from WWTPs within hydrologic unit code 10 (HUC 10) watersheds.

TDEC is utilizing the "SPARROW" model (SPARROW refers to SPAtially Referenced Regressions on Watershed attributes), which relates in-stream water-quality data to spatially referenced watershed characteristics, including contaminant sources and transport factors to support its strategy. Tennessee has aggregated the South Atlantic Gulf and Tennessee (SAGT) region model output for nitrogen and phosphorus for HUC-10 watersheds within Tennessee's borders. Thus, for West Tennessee, output from the Lower Mississippi, Arkansas-White-Red, and Texas Gulf River Basin Model (MRB5) will be applied with the focus being on agricultural reductions. However, this does not eliminate the possibility of nutrient limits in WWTP permits in future permit cycles. It is anticipated that if limits are imposed in the future, TDEC would first implement seasonal nitrification requirements (i.e., summer ammonia limits). If additional actions are deemed

necessary as the strategy is implemented, then it is anticipated that TDEC would provide these more restrictive limits (total nitrogen or total phosphorus limits) in a phased approach.

2.1 Existing Capacity Evaluation

The current average flow at the plant is approximately 70 mgd, and given the influent wastewater strength, the plant is currently at or above its original design influent biochemical oxygen demand (BOD) load. With an increase to 90 mgd (design flow), the treatment objectives cannot be met with the existing plant infrastructure. Facility improvements will be required to accommodate the increased flow and load in order to meet permit requirements, as well as to provide adequate effluent quality for implementing UV disinfection, if selected as the preferred disinfection alternative.

The activated sludge process is currently operated with a low solids retention time (SRT), approximately one day, to avoid overloading the secondary clarifiers. While the plant is generally able to achieve permit requirements using this approach, this mode of operation is unstable and does result in episodic permit excursions with respect to TSS. However, based on current biotower performance with respect to soluble BOD removal, it is not possible to increase the SRT with the existing volume in the aeration tanks (even including the volume that was originally designed as aerobic digesters), which are undersized to handle the design flow from the biotowers at the current loading rate, without overloading the secondary clarifiers.

On August 27th, 2013 CDM Smith facilitated a workshop with City staff to discuss current plant operations and potential technologies appropriate for application at the facility to meet treatment requirements. Several process alternatives were discussed and the alternatives were narrowed to the most feasible options. **Figure 2-1** provides a summary of the processes to be evaluated; because each unit process option impacts the next downstream process, alternatives are presented as a decision tree. For example, if the existing biotowers process would remain, then a decision would need to be made whether it is more cost effective to add intermediate clarifiers or additional aeration basin volume. In summary, three comprehensive process alternatives have been evaluated and the results of that analysis are provided in this memorandum.

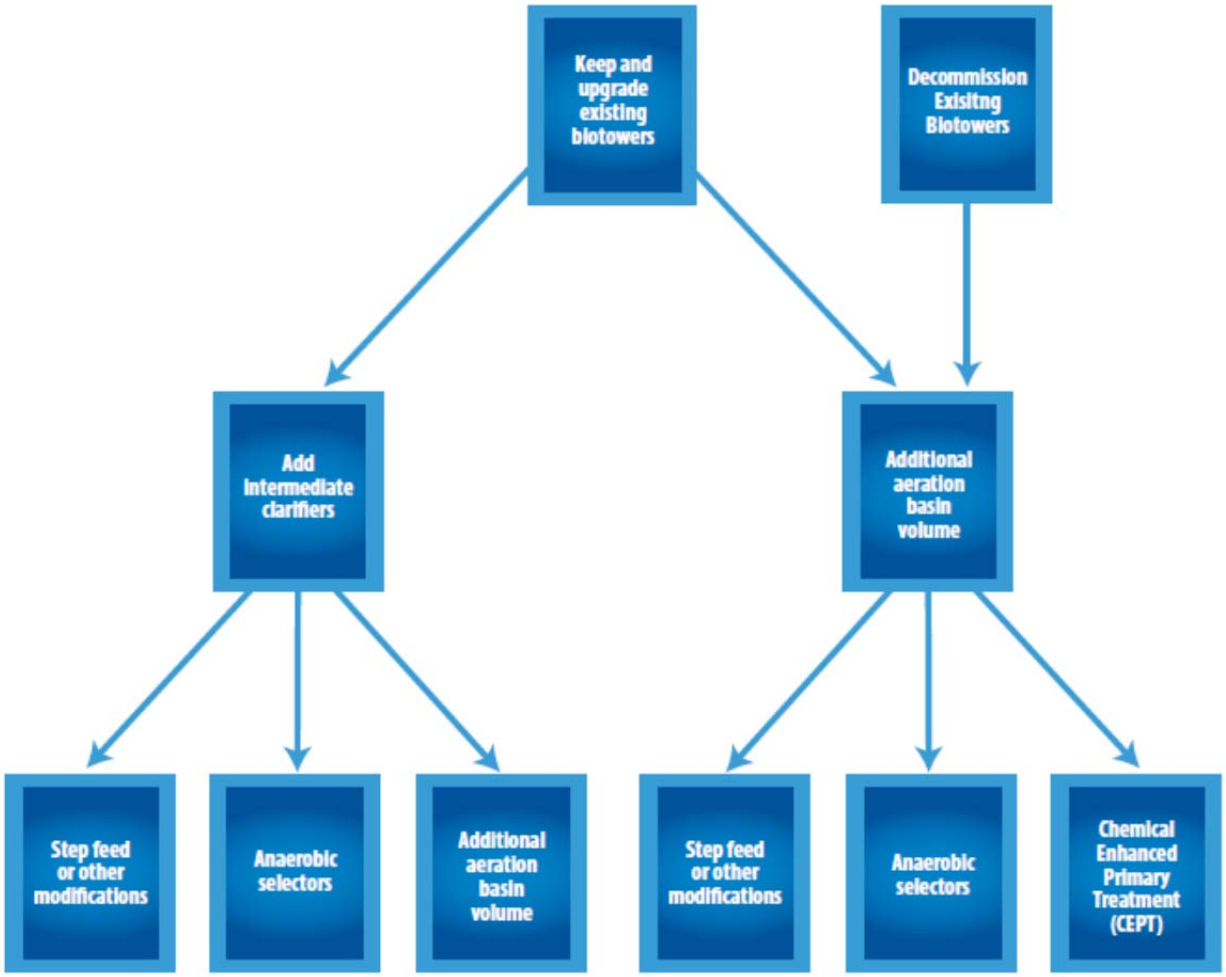


Figure 2-1 Alternatives Evaluation Decision Tree

2.2 Biotower Evaluation

With respect to the decision to keep or eliminate the existing biotowers, CDM Smith evaluated the performance of the original biotower media and compared performance to that reported for new plastic media, based on the projected loading to the process. Four biotowers were constructed in 1984 with redwood media; two additional biotowers were installed in 1997 with western cedar media. The media is past its anticipated service life and the possibility of structural failure and collapse of the media support structure presents an ongoing risk.

The performance of the biotowers could be improved by replacing the original media with new media. New media provides a significant increase in the surface area for biofilm growth, resulting in more efficient soluble BOD removal. A comparison of the soluble BOD removal by the existing original media and the anticipated removal by new media is shown in **Figure 2-2**. The performance of new media is based on modeling runs completed by Brentwood Industries using their Cross-

Flow Plastic Media. To meet the treatment objectives at the design flows and loads using the existing biotowers (if they remain) it will be necessary to replace the media. The impact of the biotowers on the aeration basin loading and resulting improvements are evaluated and discussed in Section 3.0.

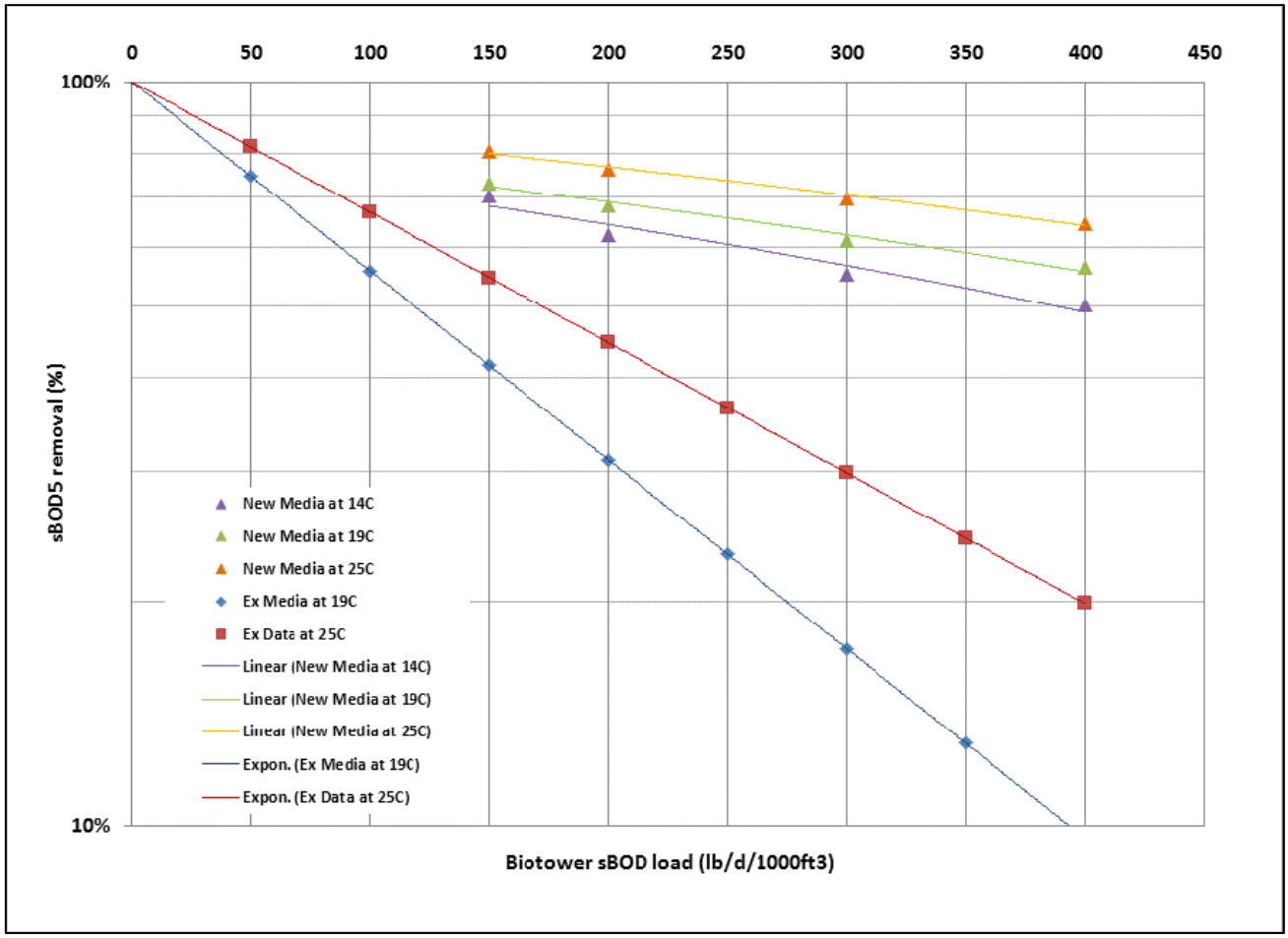


Figure 2-2 New and Existing Media Biotower Performance (% sBOD removal versus sBOD load)

3.0 Treatment Alternatives

Three treatment alternatives have been identified for detailed evaluation based on the decision tree presented in Figure 1. The requirements of each alternative are described in this section. The evaluation of each alternative includes a description of the required modifications to the liquid process train to meet the current draft NPDES permit requirements over the range of flows and loads associated with an average design flow of 90 mgd (no nitrification), and meet the TSS requirement of less than 30 mg/L on a consistent basis, for UV disinfection. In order to provide a stable activated sludge process, a minimum SRT of 2 days was selected as the basis of design. The implications with respect to the solids handling process are noted under each alternative, but

upgrades to accommodate the additional sludge handling has not been included in this evaluation. It is recommended that the City review the solids handling processes if process improvements are advanced beyond the conceptual stage.

3.1 Alternative 1: Abandon Existing Biotowers and Expand Activated Sludge Process

Alternative 1 includes abandoning the biotowers in place and expanding the activated sludge process to meet treatment requirements. CDM Smith developed a desktop tool that was utilized to determine the loading to the activated sludge process without the soluble BOD removal provided by the biotowers, so that process modifications could be identified to address future flows and loads associated with a design capacity of 90 mgd.

The average daily design flow, including sidestream recycle, to the activated sludge process is 95.8 mgd with an ADMM BOD load of 485,000 pounds per day (ppd) and a TSS load of 297,000 ppd. With an aerobic SRT of 2 days and a mixed liquor suspended solids (MLSS) of 3,400 mg/L, 29.7 million gallons (MG) of aerobic tank volume is required. The existing aeration basins provide 18.5 MG of aerobic tank volume, requiring an additional 11.2 MG to be constructed. New aeration basins would operate similarly to the existing system, i.e., in two-pass plug flow mode. As an alternative to this bioreactor configuration, the existing and new tankage could be modified to operate in step-feed mode, which would require less aerobic volume; however, step-feed would require modification of the tanks to accommodate multiple feed points. The total aeration tank volume required for step-feed operation is 24 MG (versus 29.7 MG in conventional mode), which would require an additional 5.5 MG of tankage to the existing system to be constructed (footprint 50,000 square foot (SF)) instead of the 11.2 MG required for the conventional mode.

To provide adequate clarification with one unit out of service, 12 secondary clarifiers are required, assuming a sludge volume index (SVI) of 150 milliliters per gram (mL/g). This SVI is characteristic of a well-settling biomass and in order to consistently achieve this level of performance, an anaerobic selector should also be anticipated as part of this alternative. Selectors have established proven performance at many operating plants. The preliminary sizing of an anaerobic selector, based on a hydraulic retention time (HRT) of 1 hour (forward flow only) is 3.8 MG; the selector would be included between the primary clarifiers and aeration tanks.

The return activated sludge (RAS) capacity recommended for this scenario is 100% of the average flow (or 90 mgd). The existing RAS pumping system has a capacity of 104 mgd with all pumps in service; however, due to the proposed location of the new clarifiers it is recommended that a new RAS pump station be constructed and dedicated to these clarifiers. The total solids from primary sludge, combined with the waste activated sludge (WAS), are approximately 641,000 ppd, or 3.6 dry tons per mgd, on an ADMM basis. The increase in WAS can be accommodated using an additional pump with disposal to the existing lagoons. The increase in primary sludge may require longer operation of the solids handling process with the existing belt filter presses (BFP), or require additional units to be installed.

Expanding the existing activated sludge process to accommodate these loads would require construction of additional aeration tanks, a new blower building, an anaerobic selector, secondary clarifiers, and RAS and WAS pumps housed in a new pump station. This alternative would also include removal and disposal of the media in the biotowers, though the structures would not be demolished, but instead abandoned in place. It is recommended that the biotower structures not be demolished as the space is not required for other needs at this time and they could be used in the future if required to meet increased loading or future ammonia limits requiring nitrification be added to the process. **Table 3-1** provides a summary of process upgrades to implement this alternative. The analysis conducted for Alternative 1 assumes that additional blowers, clarifiers and pumps would be provided in a configuration similar to conventional plug-flow treatment.

Table 3-1 Expand Activated Sludge Process, No Biotowers

Process Upgrades	Future Required	Existing	New Construction
Aeration			
Aeration Tank Volume (MG)	29.7	18.5	11.2
Anaerobic Selector Tank Volume (MG)	3.8	0	3.8
Aeration Tank Footprint (SF)	265,000	165,000	100,000
Air Requirement (SCFM)	335,000	240,000	95,000
Total Blower HP	19,000	9000	10,000
Total Number of Blowers	10 total 9 duty	6	4
Clarification			
Secondary Clarifier Units (135 FT Diameter)	12	8	4
Solids			
WAS Pumping Capacity (MGD)	13.5 total 9.0 duty	9.0	4.5
Total Number of WAS Pumps	3	2	1
RAS Pumping Capacity (MGD)	125 total 90 duty	104	21
Total Number of RAS Pumps	8 total 6 duty	6	2
Total Solids Production (ADMM PPD)	641,000	NA	NA
Total Solids Production (DT/MGD)	3.6	NA	NA

3.2 Alternative 2: Upgrade Biotowers and Add Intermediate Clarifiers

Upgrading the existing biotowers with new media would significantly increase their performance as noted earlier. The biotowers could remove more soluble BOD; however, increased solids concentrations in the biotower effluent would occur because of increased biomass production and resultant sloughing. These solids, if not removed, would increase the solids loading to the aeration tanks and significantly impact the activated sludge process capacity. To avoid construction of additional aeration tankage and upgrades to the ancillary systems to accommodate these solids, intermediate clarifiers could be added downstream of the biotowers.

Conceptually, six (6)164-ft diameter intermediate clarifiers would provide a surface overflow rate (SOR) of 706 gallons per day per square foot (gpd/sf) at average daily flow (ADF) and would remove an estimated 330,000 ppd day of solids. The resultant ADMM load to the downstream activated sludge process would be 166,000 ppd BOD and 26,000 ppd TSS. With an aerobic SRT of 2 days the existing aeration tank volume is adequate for treatment operating at a MLSS concentration of 1,600 mg/L, requiring no upgrade to the tank volume or the air supply system. The aeration tank volume required for this scenario at a MLSS of 1,600 mg/L is 18.5 MG. In addition, there is sufficient spare volume within the existing aeration tanks to insert an anaerobic selector, sized at 3.8 MG, negating the need to build a new structure for the selector. Incorporating an anaerobic selector into the existing tankage would result in remaining aerobic volume of 14.7 MG and a resulting MLSS concentration of 1,900 mg/L. In addition, due to the lower required MLSS concentration and the reduced solids load to the clarification process, the existing 8 secondary clarifiers and sludge pumping capacity are adequate. The existing clarifiers, with one unit out of service, with a SVI of 150 mL/g, provide a SOR of 900 gpd/sf and a solids loading rate (SLR) of 24 ppd/sf at ADF without the selector and 29 ppd/sf at ADF with the selector . The total solids produced, including primary sludge, intermediate sludge and WAS is approximately 816,000 ppd, or 4.5 dry tons per mgd on an ADMM basis.

This alternative would require media replacement in all six biotowers, biotower odor control, six 164-ft new intermediate clarifiers and an intermediate sludge pump station. The overall depth of the media in the biotowers would be reduced from 21 feet to approximately 18 feet and the floor of the biotowers could be raised to avoid construction of an intermediate pumping station to pump flow to the aeration tanks.

Table 3-2 presents a summary of process upgrade requirements to implement Alternative 2.

Table 3-2 Upgrade Biotowers and Add Intermediate Clarifiers

Process Upgrades	Future Required	Existing	New Construction
Biotowers			
No. Units (135 FT Diameter)	6	6	0
Media Depth (FT)	18	21	18
Odor Control			
Air Requirement (SCFM)	180,000	0	180,000
Total Fan HP	600	0	600
Intermediate Clarification			
Intermediate Clarifier Units (164 FT Diameter)	6	0	6
Anaerobic Selector			
Tank Volume carved out of existing aeration tank (MG)	3.8	0	3.8 (modified existing)
Solids			
Intermediate Sludge Pumping Capacity (MGD)	2.3 total 2.0 duty	0	2.3
Total Number of Pumps	7 total 6 duty	0	7
Total Solids Production (PPD)	816,000	NA	NA
Total Solids Production (DT/MGD)	4.5	NA	NA

Notes:
1. Odor Control requirements based on V&A Report.

Alternative approaches to providing odor control for the biotowers have not been evaluated in this memorandum; odor control was the subject of a separate evaluation recently conducted by V&A. However, should Alternative 2 be selected and advanced to the conceptual design stage, it is suggested that alternative odor control approaches be carefully considered. One option that has been considered for similar applications includes capture of odorous air, and diffusing it into the activated sludge system. This accomplishes two goals: 1) treatment of odor in the aerobic biological process in the aeration tanks; and 2) use of the ventilated air stream as the source of process oxygen. While this odor control approach has merit, and has been successfully used at other facilities, there are several aspects of the approach that are disadvantages and need to be carefully considered. These include:

- The condition/characteristics of the odorous air and the impact of contaminants in the air stream on the process, including condensate handling.
- The material specifications (and cost) that may be required to provide process blowers that can suitably compress the odorous air to the required pressure.

- The potential constraints this approach may place on the ability to adequately control dissolved oxygen in the process tanks, due to the inability to turn down the ventilation rate of the odor control system.

3.3 Alternative 3: Utilize CEPT, Upgrade Biotowers and Expand Activated Sludge Process

Alternative 3 includes addition of chemical enhanced primary treatment (CEPT), upgrade of the biotowers with new media, and expansion of the activated sludge process. In this alternative, additional solids would be removed in primary treatment, reducing the load on the biotowers and the downstream activated sludge process. Additional aeration tank volume would be required, but at a lower volume than Alternative 1.

By adding CEPT, the solids and organic loading to the biotowers could be reduced. The biotowers would be upgraded with new media to further reduce soluble BOD loading to the activated sludge process. As a result, the load to the activated sludge process would be 335,000 ppd BOD and 336,000 ppd TSS under ADMM loading conditions. With an aerobic SRT of 2 days and a MLSS of 3,100 mg/L, the total aeration tank volume required is approximately 24 MG. The existing aeration basins provide 18.5 MG of aerobic tank volume, requiring an additional 5.7 MG to be constructed. Similar to Alternative 1, 12 secondary clarifiers would be required to provide adequate clarification and a new 3.8 MG tank is required for the anaerobic selector. Also similar to Alternative 1, step-feed could be implemented and would require slightly less aerobic volume than plug-flow tanks. Modifications to the existing aeration tanks would be required to accommodate multiple feed points. Additional blowers, clarifiers, and pumps would be the same as for conventional treatment. The total aeration tank volume required for step-feed is 19.6 MG (vs. 24.2 MG for conventional), which would require an additional 1.1 MG of tankage be constructed (footprint of 10,000 SF) instead of the 5.7MG required for the conventional mode.

The required RAS rate for this scenario is 82% of the average flow or 74 mgd. The existing RAS pumping system has a capacity of 104 mgd with all pumps in service; however, due to the proposed location of the new clarifiers it is recommended that a new RAS pump station be constructed and dedicated to these clarifiers. The total solids produced, including primary sludge and WAS, is approximately 726,000 ppd or 4.0 dry tons per mgd on an ADMM basis. The increase in WAS can be accommodated using an additional pump with disposal of biosolids to the existing lagoons. The increase in primary sludge may require longer operation of the solids handling process with the existing belt filter presses (BFP) or require additional units to be installed. The inert chemical solids from the CEPT process would not be biodegraded in the lagoons, and the impacts of the additional inert materials would have to be evaluated, particularly in light of the ongoing work on Lagoon #5. As a result, the chemical sludge from the primaries may require an alternate disposal method.

This alternative would require a chemical feed system and building, media replacement in all six biotowers, biotower odor control, additional aeration tanks and one new blower, secondary

clarifiers, and RAS and WAS pumps. **Table 3-3** presents a summary of process upgrade requirements to implement Alternative 3.

Table 3-3 CEPT, Biotower & Activated Sludge Upgrades

Process Upgrades	Future Required	Existing	New Construction
CEPT			
Chemical Feed System (ferric chloride) - Four 9,000-gal FRP storage tanks with pumps and controls	1	0	1
Chemical Feed System Building (SF)	2400	0	2400
Biotowers			
No. Units (135 FT Diameter)	6	6	0
Media Depth (FT)	21	21	21
Odor control			
Air Requirement (SCFM)	180,000	0	180,000
Total Fan HP	600	0	600
Aeration			
Aeration Tank Volume (MG)	24.2	18.5	5.7
Anaerobic Selector (MG)	3.8	0	3.8
Aeration Tank Footprint (SF)	215,000	165,000	50,000
Air Requirement (SCFM)	246,000	240,000	6,000
Total Blower HP	14,000	9,000	5,000
Total Number of Blowers	7 total 6 duty	6	1
Clarification			
Secondary Clarifier Units (135 FT Diameter)	12	8	4
Solids			
WAS Pumping Capacity (MGD)	13.5 total 9 duty	9	4.5
Total Number of WAS Pumps	3	2	1
RAS Pumping Capacity (MGD)	125 total 90 duty	104 total	21
Total Number of RAS Pumps	8 total 6 duty	6	2
Total Solids Production (PPD)	726,000	NA	NA
Total Solids Production (DT/MGD)	4.1	NA	NA

4.0 Conceptual Layouts of Alternatives

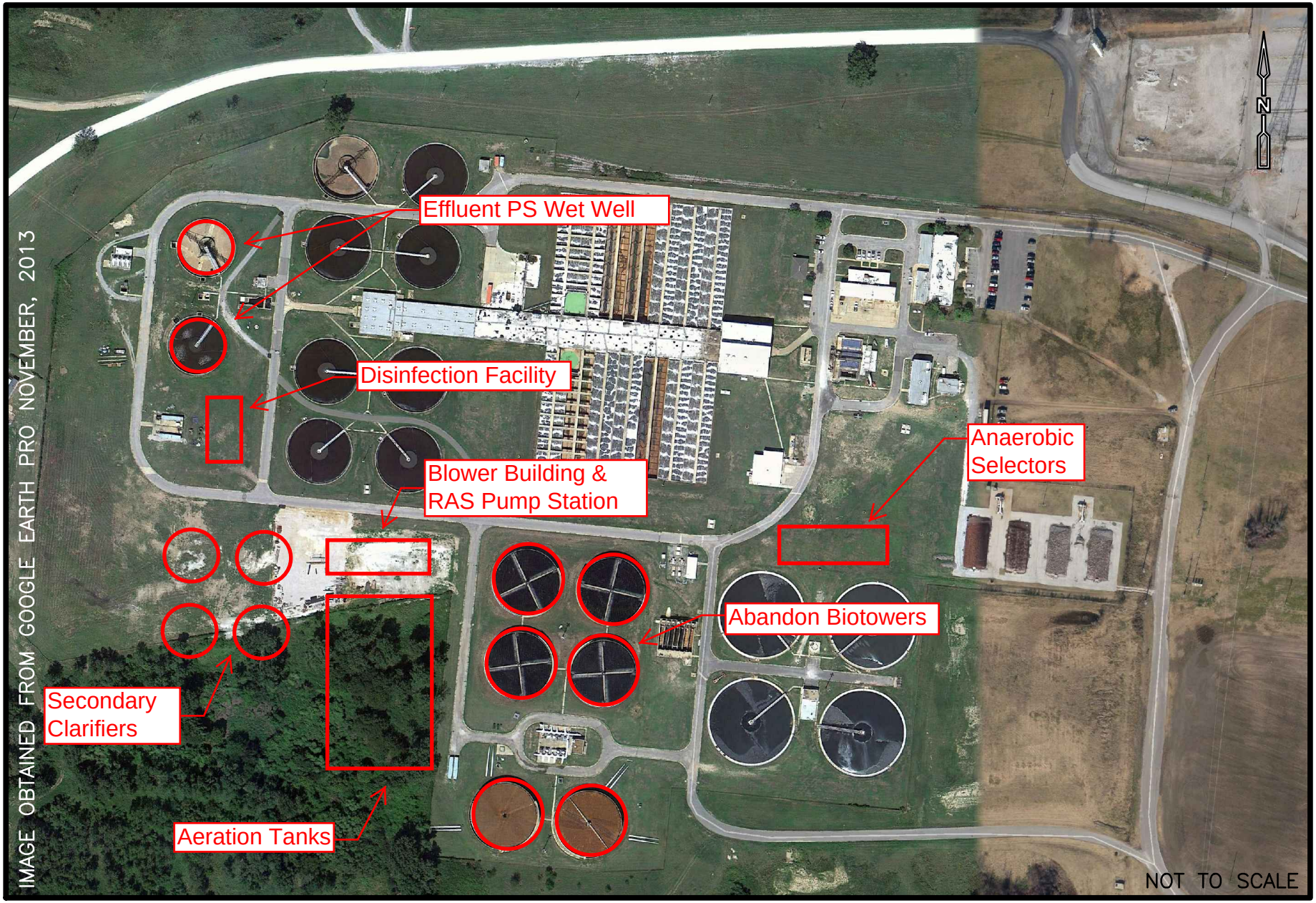
This section presents conceptual level layouts for each alternative. In addition to addressing process modifications for each alternative, the layouts identify a location for the effluent pump station wet well and disinfection facilities, which have been evaluated separately as part of the disinfection study and would be incorporated into the upgrade alternatives.

4.1 Alternative 1: Abandon Existing Biotowers and Expand Activated Sludge Process

Figure 4-1 shows a conceptual layout for Alternative 1 – abandoning the existing biotowers and expanding the activated sludge process as described in Section 3.1. The existing biotower media would be removed and disposed of at a landfill. In order to provide a 3.8 MG anaerobic selector, an approximate footprint of 256 ft x 128 ft would be required for a new basin with a sidewater depth of 15 ft. An additional 11.2 MG, or 100,000 square feet of aeration tank volume (operated in conventional mode), would be required for this alternative and has been preliminary shown west of the biotowers. The two retrofitted clarifiers (Nos. 5N and 5S) would not be used due to hydraulic issues and the space could be repurposed as wet wells for the effluent pump station. Four additional new clarifiers are required and could be located adjacent to the new aeration tanks. The existing blower and RAS buildings do not have adequate space to accommodate additional equipment and a new building is required; the blower and RAS building has been shown adjacent to the new aeration tanks and clarifiers. The disinfection facility would be located between the two sets of secondary clarifiers as a central point for the secondary effluent to combine and be treated.

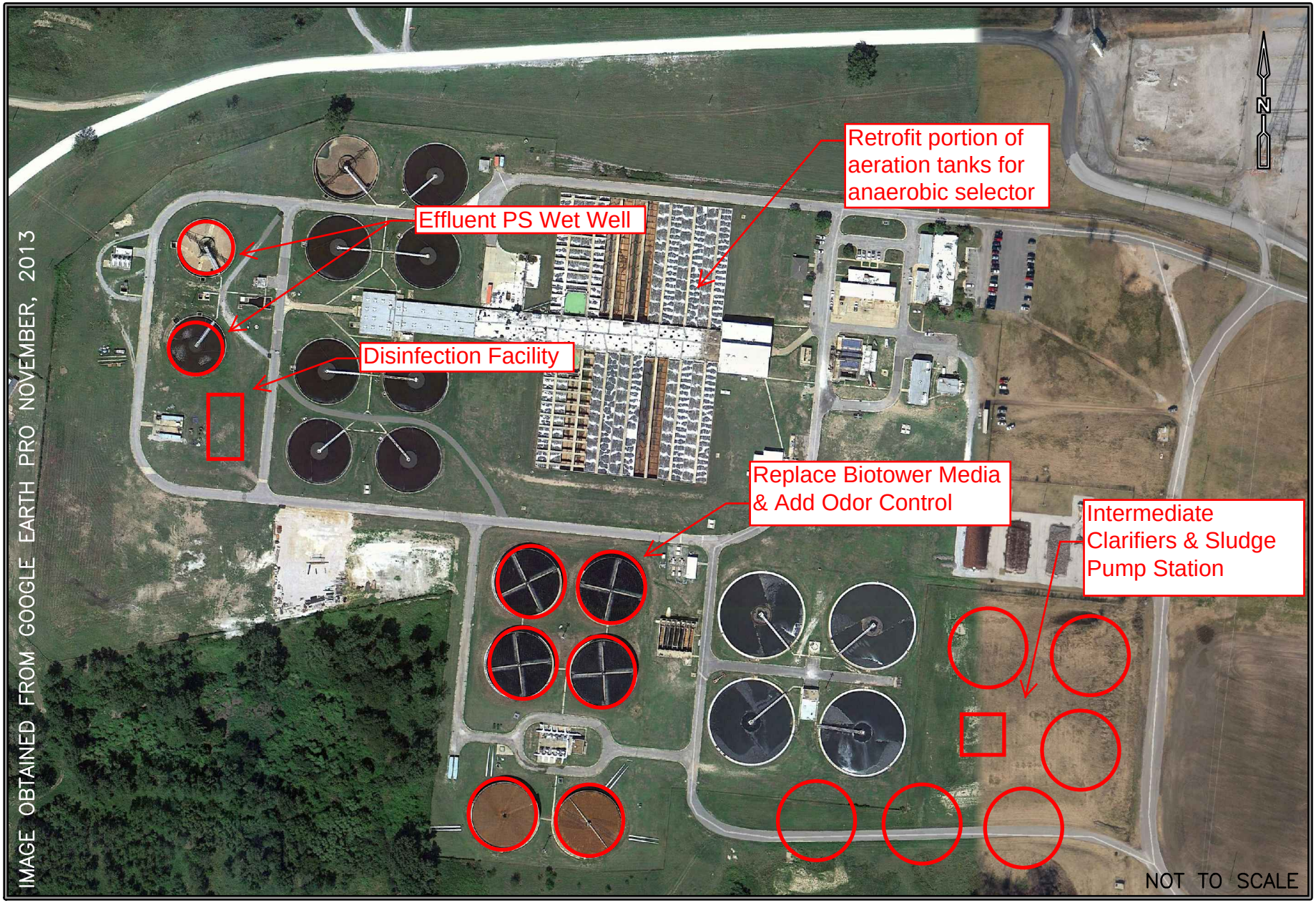
4.2 Alternative 2: Upgrade Biotowers and Add Intermediate Clarifiers

Figure 4-2 shows a conceptual layout for implementing Alternative 2 – upgrading the biotowers and adding intermediate clarifiers. The existing biotowers would remain and the media would be replaced with “cross flow” type high-surface area media, as manufactured by Brentwood Industries or equivalent. An odor control system would be provided to treat air from the biotowers and this system would be located adjacent to the biotowers. Six intermediate clarifiers would be required to remove solids prior to the activated sludge process and could be located to the east of the existing biotowers. To avoid the need to pump wastewater from the intermediate clarifiers to the aeration tanks, the biotower filter depth would be reduced from the current depth of 21-ft to 18-ft and the floor of the existing structures would be raised. A sludge pump station to convey the settled solids from the clarifiers to the solids handling process would need to be constructed adjacent to the intermediate clarifiers. No new aeration tank volume would be necessary, and there would be sufficient volume in the existing aeration tankage to convert 3.8 MG into an anaerobic selector. The two retrofitted clarifiers (Nos. 5N and 5S) would not be reused and the space could be repurposed for wet wells to the effluent pump station. The disinfection facility would be located west of the secondary clarifiers at the end of the treatment process.



CDM Smith

Figure No. 4-1
Alternative No. 1
NOVEMBER 2013



CDM Smith

Figure No. 4-2
Alternative No. 2
NOVEMBER 2013

4.3 Alternative 3: Utilize CEPT, Upgrade Biotowers and Expand Activated Sludge Process

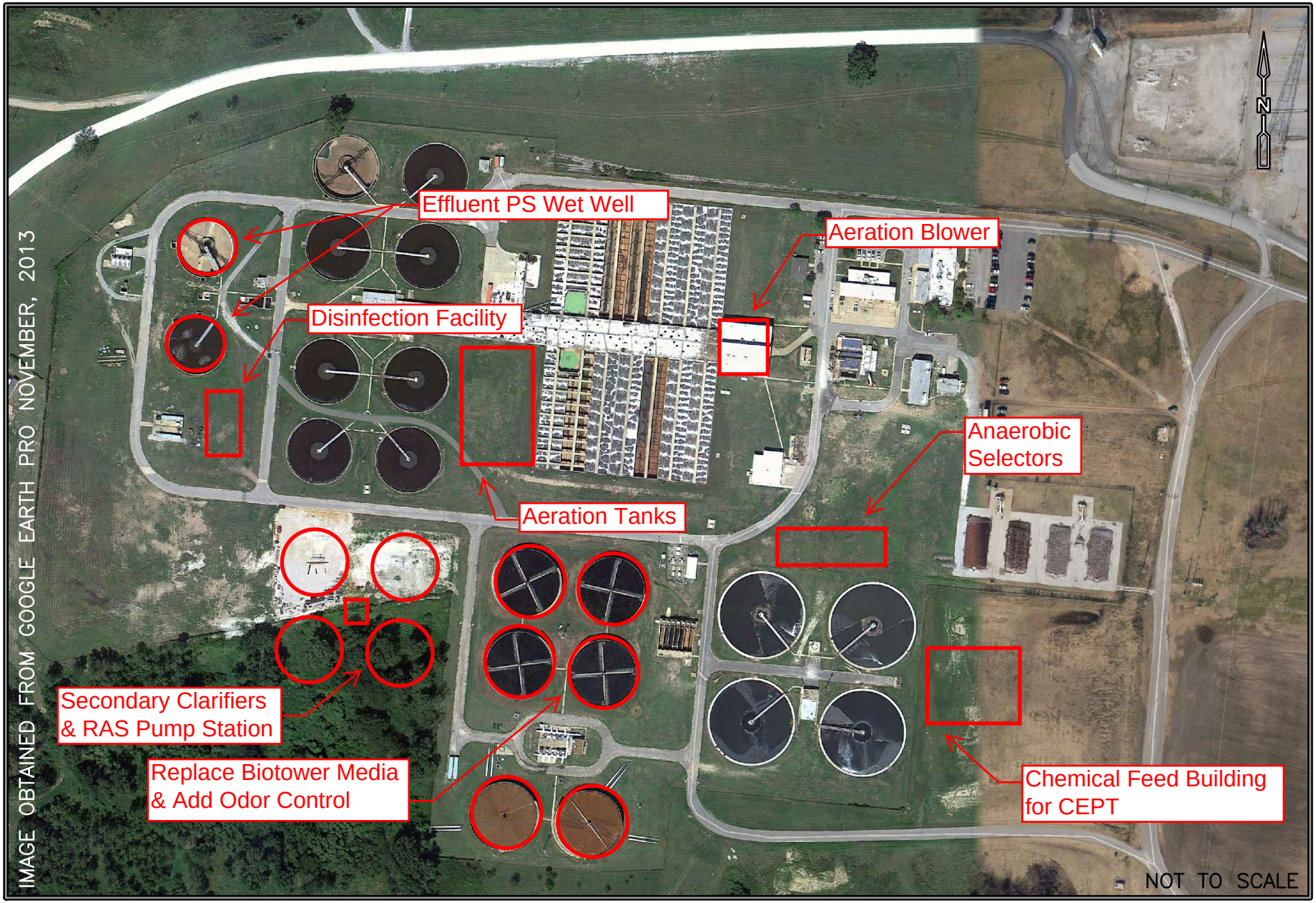
Figure 4-3 shows a conceptual layout for Alternative 3 – utilizing CEPT with upgrades to the biotowers and the activated sludge process. To implement the CEPT process, a chemical feed system would be required in a new building located just to the east of the primary clarifiers. The building would be located adjacent to a plant driveway to facilitate chemical deliveries (assumed to be ferric chloride for this analysis). The CEPT building would house chemical storage tanks, pumps and ancillary mechanical, electrical and instrumentation equipment. The existing biotowers would remain and the media would be replaced with new high-surface area media (as noted in Alternative 2). The biotower depth would remain at 21-ft deep. An odor control system would be provided to treat air from the biotowers; the odor control facility would be located adjacent to the biotowers. A 3.8 MG anaerobic selector, approximate footprint of 256 ft x 128 ft, would be required. An additional 5.7 MG of aerobic volume is required for the activated sludge process and could be located adjacent to the existing tanks. The two retrofitted clarifiers (Nos. 5N and 5S) would not be reused and the space could be repurposed as wet wells for the effluent pump station. Four additional clarifiers are required and could be located adjacent to the biotowers. Due to hydraulic constraints and lack of space in the existing RAS building, a new pump station would be located central to the new clarifiers. The disinfection facility would be located west of the secondary clarifiers at the end of the treatment process.

5.0 Engineer's Opinions of Probable Costs

5.1 Basic Assumptions

For this study, probable capital (construction) costs were estimated based on vendor quotes, estimation of construction quantities and building spaces, cost information from recently completed projects and other relevant sources. Specific capital cost estimating factors include indirect costs, contractor's general conditions, contractor's overhead and profit, contingencies, and engineering and implementation. Indirect costs include costs associated with permits, sales tax, insurance and bonds. Adjustments and changes made during subsequent stages of design would affect the estimates, as would future escalation in the cost of materials, labor, and equipment. Specific capital cost factors used in this memorandum to calculate the probable costs include:

Construction Contingency	30 percent
Contractor GC Field General Conditions	10 percent
Contractor GC Indirects, Overhead & Profit	10 percent
Contractor Bonds and Insurance	3.65 percent
Planning, Design and Construction Services	10 percent
Utility Administration, Legal, bonds & Insurance	3 percent



CDM Smith

Figure No. 4-3
Alternative No. 3
NOVEMBER 2013

5.2 Opinion of Probable Project Costs

The capital construction costs for each alternative include the process modifications as described in the previous sections. In addition to the process modifications, estimated costs for potential electrical modifications required to support the process modifications and to retrofit the effluent pump station and wet well were included; however, no actual electrical evaluation or recommendations were completed. The electrical costs included are estimated based on past relevant projects. For planning level purposes, the electrical upgrades have been estimated at 10 percent of the direct construction cost. For each alternative placeholders of $1 million and $3 million, respectively, have been allocated to account for the provision of a new or modified effluent pump station wet well (as an actual design concept was not completed as part of this study) as well as the addition of an anaerobic selector for biological treatment as part of each of the alternatives as discussed above. **Table 5-1** provides a summary of the Opinion of Probable Project Cost (OPPC) for each alternative.

Table 5-1 Opinion of Probable Project Cost

Alternative	Description	Individual OPPC
1	No Biotowers Expand Activated Sludge Process	$78,000,000 Conventional ($68,000,000 Step Feed)
2	Upgrade Biotowers & Activated Sludge Process	$82,000,000
3	CEPT, Upgrade Biotowers & Activated Sludge Process	$104,000,000

For Alternative 1, which does not utilize the existing biotowers, it was assumed that the biotower media would be removed and disposed of at a landfill and the towers would be abandoned in place. No cost was added for demolition of the tower structures; it is recommended that the structures be abandoned in place as the space is not needed at this time for other purposes. Also, it allows for the biotowers to be put back in operation in the future if the loading conditions change. In addition, the capital cost for the odor control system identified in the August 14, 2013 V&A technical memorandum is included in both Alternatives 2 and 3 at the previously identified cost of $7.2 million. CDM Smith has not independently verified the sizing of this facility or the line item cost.

5.3 Comparative Operational Costs

To compare the approximate differences in operational costs among alternatives, chemical, power, and labor costs associated with each alternative have been developed and are presented in **Table 5-2**. Cost assumptions used in this evaluation include:

Power $0.076 per kilowatt-hour (kWh)

Labor Rate $40/hr.

Ferric chloride ($FeCl_3$) $1.06/gal (obtained verbally from Kemira for 36% solution)

Table 5-2 Comparative Annual Operating Costs

Alternative	Description	Labor Cost	Power Cost	$FeCl_3$ Cost	Comparative Cost
1	No Biotowers Expand Activated Sludge Process	$0	$5,400,000	$0	$5,400,000
2	Upgrade Biotowers & Activated Sludge Process	$17,000	$4,200,000	$0	$4,217,000
3	CEPT, Upgrade Biotowers & Activated Sludge Process	$250,000	$5,700,000	$2,100,000	$8,050,000

Notes:
1. Operational costs are for alternative comparison only and do not reflect total plant operating cost.

Power costs are differential costs, based on major motor loads that are included in one or more alternatives. The power costs do not include those that apply equally to all alternatives. The process equipment considered for the comparative power consumption includes:

CEPT chemical feed system

Intermediate pump station (from primary clarifiers to biotowers)

Biotower recirculation pumps

Biotower odor control fans

Intermediate clarifiers

Intermediate sludge pumps

Aeration tank blowers

Secondary clarifiers

RAS and WAS pumps

For aeration blower power estimates, horsepower requirements were estimated based on average day demand (at 90 mgd), assuming six months per season based on winter and summer air requirements. The biotower odor control fans were based on a ventilation rate of 30,000 cubic feet per minute (cfm) per biotower, as determined by V&A Consultants in a technical memorandum dated August 14, 2013. The horsepower requirements for the odor control fans were not included in the V&A evaluation; CDM Smith estimated power based on the air requirement determined by V&A to be 100 horsepower (hp). If odor control is to be implemented, the horsepower requirement would be confirmed during subsequent stages of more detailed engineering. The cost of odor control media replacement for the odor control biofilters has not been included in this evaluation. The V&A report indicates that the City may own a low- or no-cost source of media, but it should be noted that the media may need to be replaced every 3-6 years depending on loading to the process. As previously discussed, solids handling has not been included in this evaluation and the associated impacts to operations has not been included in these costs.

5.4 Summary of Life Cycle Costs

The approximate difference in life cycle costs associated with each alternative has been developed and is presented in **Table 5-3**. The lifecycle cost includes the OPCC for construction and the annual operating costs summarized in Table 5-2. Assumptions used in this evaluation include:

Planning period	20 years
Discount rate	4.13 percent
Inflation rate	3.00 percent
Power escalation rate	2.00 percent

Table 5-3 provides a summary of the lifecycle costs of the three alternatives and indicates that Alternative 1 has the lowest capital cost and the 20-year present worth of this alternative with higher operations costs makes Alternative 2 a viable option as well. The power requirement for aeration is the significant operating cost for Alterative 1. Utilizing CEPT (Alternative 3) has both a high capital cost and a high operations cost, primarily due to the need to implement capital improvements in primary treatment, biotowers upgrades and the activated sludge process. Additional chemical requirements also significantly impact the operations costs of Alternative 3.

Table 5-3 Total 20-Year Life Cycle Comparison of Alternatives

Alternative	Description	Capital Cost (OPPC)	20 Year Operations Present Worth	20 Year Total Present Worth
1	No Biotowers Expand Activated Sludge Process	$78,000,000 Conventional ($68,000,000 Step Feed)	$118,000,000	$196,000,000 Conventional ($186,000,000 Step Feed)
2	Upgrade Biotowers & Activated Sludge Process	$82,000,000	$92,000,000	$174,000,000
3	CEPT, Upgrade Biotowers & Activated Sludge Process	$104,000,000 ($94,000,000 Step Feed)	$167,000,000	$271,000,000 ($261,000,000 Step Feed)

5.5 Recommendations

Although a solids handling evaluation was not completed, impacts to the solids handling operations should be considered and fully understood in determining a recommended approach for expanding the WWTP. The operation for solids handling for Alternative 1 and 2 would remain essentially the same as the current operation, with biological solids pumped directly to the lagoons and primary sludge dewatered and discharged to the lagoons. The existing belt filter presses may be adequate for dewatering the increased solids by extending the hours of operation or installing additional units. Alternative 3, CEPT with activated sludge process, produces two types of sludge; an additional chemical sludge is produced from the CEPT process and will require that the sludge be disposed of separately from the biological sludge.

Due to the high capital and operations costs of Alternative 3 coupled with the potential complexities associated with handling inert solids from the CEPT process, this option is not considered a viable alternative and can be eliminated from further evaluation. Alternative 1 and 2 are both feasible options that provide their own benefits to the WWTP. A summary of the advantages and challenges of each of these two alternatives are summarized in **Table 5-4**.

Table 5-4 Non-Cost Comparison of Alternatives 1 and 2

	Alternative 1	Alternative 2
Description	Abandon biotowers and expand activated sludge process.	Upgrade biotowers and add intermediate clarifiers.
Impacts to Process Configuration for Potential Future Ammonia Limit	Aerobic SRT would have to be quadrupled (to 8 days) to nitrify year-round. This would require a 4x increase in aeration basin volume to keep the same MLSS concentration of 3,400 mg/L (this assumes no additional secondary clarifiers). Final configuration with step-feed would have 96 MG of aerobic tankage and 12 secondary clarifiers. Fitting the necessary aeration tank volume on the site may be marginally feasible.	Aerobic SRT would have to be quadrupled (to 8 days) to nitrify year-round. This would require a 2.25x increase in aeration basin volume and four additional secondary clarifiers. Final configuration without step-feed and the selector inside the existing aeration tankage would have 33 MG of aerobic tankage and 12 secondary clarifiers, while increasing the MLSS from 1,900 mg/L to 3,400 mg/L. The additional requirements are less than Alternative 1 because the MLSS concentration for Alternative No. 2 can be raised to equal Alternative No. 1 to offset additional aerobic tankage.
Impacts to Process Configuration for Potential Future TN Requirements	Sufficient soluble BOD for process to be expanded would be available. Anoxic process volume would need to be added; the anaerobic selector volume could be converted to provide at least a portion of the required anoxic volume.	Biotowers would need to be removed, or at least the ability to bypass all or a portion of the flow around the biotowers would be necessary to provide sufficient soluble BOD to the activated sludge process. Anoxic process volume would need to be added; the anaerobic selector volume could be converted to provide at least a portion of the required anoxic volume.
Odor Control	Biotowers and Intermediate Pump Station not required, eliminating this specific source of odor and need for control.	Biotowers and Intermediate Pump Station remain and odor control system will be required.
Additional Capacity/ Process Flexibility	No ability to increase MLSS (3,500 mg/L) in existing tankage, 20 mg/L estimated effluent TSS. No additional process capacity available.	Lower MLSS (1,600 mg/L) requires 13.5 MG of aeration volume of the 18.5 MG available; process flexibility available to allow increase of MLSS in existing tankage; 10 mg/L estimated effluent TSS.
Maintenance of operations during construction	Existing processes can operate largely without impact during construction.	Only one biotower can be out of service at a time for media replacement.

Tables 5-1, 5-2 and 5-3 show that on an economic basis, Alternatives 1 and 2 are in the same range. Alternative 1 is more economical on a capital-cost basis, and Alternative 2 is more economical on an annual operating cost basis, and has a lower 20-year life cycle cost. Because the economics are "close", the right alternative for the plant to implement therefore must result from a considered weighing of the non-economic factors presented by each option.

The most critical non-economic consideration in deciding between Alternative 1 and Alternative 2 is the potential requirement for the plant to achieve nitrification (either year-round or seasonal) or total nitrogen removal in the future. As indicated by review of Table 5-4, if the plant is required to remove ammonia (to nitrify) in the future, then Alternative 2 would be the preferred option; however, if the plant is required to remove total nitrogen (to denitrify) in the future, then Alternative 1 would be preferred. At this time, it is unknown which, if either, of these performance requirements will become part of the plant's discharge permit.

However, it is possible to proceed with needed process upgrades now while keeping options open for meeting future permit possibilities. By selecting Alternative 1 now, the plant would implement the lowest capital cost option now, and if implemented correctly, could maintain the flexibility to best address future permit requirements for either ammonia or total nitrogen. The expansion of the activated sludge process described to implement Alternative 1, consisting primarily of new aeration tankage, clarifiers and supporting systems, would be sited and built to accommodate further expansion to meet potential future permit requirements. The biotower structures would be abandoned in place but not demolished; therefore, it would be possible to put back into operation in the future if ammonia removal is required. In addition, the siting of the Alternative 1 facilities would allow for site footprint to be allocated for intermediate clarifiers in the future (east of the biotowers as shown in Alternative 2), if total nitrogen removal is required in the future. In the event that a future nitrogen limit is required, the biotowers could then be demolished and additional aeration tankage could be constructed in this space.

Because of its flexibility to be designed and arranged to be suitable for future adaptation to either ammonia or total nitrogen limits, Alternative 1 is recommended for implementation at this time.

FMC
ENVIRONMENTAL SOLUTIONS

WATER TREATMENT

November 18th, 2013

Kati Bell, Ph.D.
CDM Smith
210 25th Avenue North, Suite 1102
Nashville, TN 37203

Re: VigorOx® WWT II Disinfection Process for the Maxson WWTP

Dear Kati,

Following our July 26th proposal for the Stiles WWTP, we would like to submit for your consideration a similarly structured proposal for the use of the VigorOx® WWTII Disinfection Process at the Maxson WWTP. The pricing approach is based on water quality parameter ranges that are expected to represent most operating conditions expected at the plant.

1. Scope of Supply

Equipment

Two (2) 40,000 gal Storage Tanks for VigorOx WWTII, including all nozzles, level instrumentation, tie-downs.
One (1) VigorOx Feed and Control System, including four (4) chemical feed pumps (two injection points), PLC-based system control panel, color touch-screen HMI, two (2) on-line PAA probes.

Disinfectant

VigorOx® WWTII Peracetic Acid, Delivered Bulk
100% of Plant Requirements during contract period

Services

Equipment Startup
Disinfectant Delivery and Tank Fill Up
Tank Level Monitoring and Delivery Scheduling
Disinfection Process Remote Monitoring
Equipment Preventive Maintenance
Equipment Corrective Maintenance

Process Guarantee

Under the full disinfection solution model, FMC guarantees compliance with the plants NPDES permit pathogen limits: (a) daily maximum and (b) 30-day geometric mean of daily grab samples. The mechanism to assess penalties for non-compliance will be negotiated with the City.

1.2 Commercial Terms

Pricing

TSS Range Bracket	Price per MGD
0 to <15	$89.00
>15 to <30	$153.00
>30 to <96	$253.00
>96	$500.00

- Price includes all items listed under '1.1 Scope of Supply'.
- Invoices will be generated monthly.
- Invoice amount will be calculated at the end of the month, by adding the month's daily totals (MGD * Price) and considering the daily average value for each of the water quality parameters to select the appropriate price tier.
- Flow rate, Color and TSS are to be measured continuously and on-line; instruments to be calibrated periodically by a third party.
- Pricing also assumes influent pathogen count will not exceed $1x10^6$ CFU/100ml.
- Pricing and calculations are based on a minimum contact time of 15 minutes

Contract Duration

- Minimum contract duration: 5 yrs

Evaluation Period

- Understanding that the pricing above is based on limited data, FMC proposes to establish a six month evaluation period in which real plant conditions and disinfectant demand can be properly evaluated. After this six month period, both the City of Memphis and FMC will have the right to renegotiate price or terminate the contract if agreement on pricing cannot be reached.

All other terms and conditions will be negotiated with the City of Memphis.

This pricing is provided for CDM Smith's use in connection to the City of Memphis' Stiles WWTP project only, and we ask that these price ranges are treated as confidential information that should not be disclosed to any third parties, other than CDM Smith's client for this project.

Best regards,

Alberto Garibi
Business Manager, Water Treatment

DRAFT
REPORT

Maxson WWTP
Supplemental Pilot & Bench Disinfection Testing Report

City of Memphis, TN

January 2016

CDM Smith

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Executive Summary

The City of Memphis has been evaluating various disinfection alternatives for use at the T.E. Maxson Wastewater Treatment Plant (Maxson) over the past several years. Since the previous pilot work, performed by CDM Smith in 2013, two major changes have occurred at Maxson. First, during the 2013 pilot testing, a portion of the plant treatment process was being bypassed to allow for the construction/installation of the new fine screen facility prior to the primary clarifiers. Second, a major industrial contributor (Cargill) to Maxson closed and was anticipated to result in a significant reduction in overall plant loading. As a result, supplemental pilot testing of peracetic acid (PAA) was performed at Maxson. In addition, supplemental UV related analysis were performed, as was bench testing the utilization of UV and PAA as a combined disinfectant.

This report provides a summary of on-site pilot testing and development of the disinfection kinetics model for establishing design criteria for a PAA disinfection system. The kinetic model allows selection of design doses for a range of contacts times and bacterial inactivation set points. Updated design criteria for a UV system, based on new collimated beam data, were also developed. In addition to the PAA pilot study results, results from bench scale testing of UV/PAA combined testing are also reported.

The key objectives of the additional pilot testing conducted were aimed at supplementing the bench and pilot testing that have previously been conducted at the Maxson WWTP. In order to confirm the results of previous testing, in light of the recent changes at the facility, the following objectives were addressed with respect to meeting limits for *Escherichia coli* (*E. coli*) as outlined in the current draft National Pollutant Discharge Elimination System (NPDES) permit:

- Refine the design criteria for PAA disinfection to meet disinfection limits
    - Determine the kinetic model parameters to predict PAA disinfection efficacy across a range of doses and contact times
    - Determine the design dose for average conditions to support calculation of associated operating costs
- Confirm the UV disinfection design dose to support estimates of capital and operating costs

The key objectives of the bench scale UV/PAA disinfection study included:

- Quantify and compare disinfection kinetics among several UV and PAA combinations including:
    - PAA alone, UV alone, UV followed by PAA, PAA followed by UV, simultaneous disinfection with UV and PAA.
- Propose a mechanistic model to describe the efficacy of the combined disinfectant

PAA pilot testing commenced on Monday, May 4th, and continued through Friday, June 5th, 2015; samples were collected and submitted to Environmental Testing and Consulting Laboratory,

located in Memphis, Tennessee. Results and analysis of data are provided in this document. The disinfection kinetics model that was developed allowed CDM Smith to make recommendations on both UV and PAA design criteria and directly compare lifecycle costs for the two disinfection alternatives.

Three disinfection set points were established to reflect average, peak, and minimum conditions at the plant. The basis for these set points are described in Section 3. **Table ES-1** shows the results of the PAA pilot results analysis for each of the disinfection set points in the terms of CT. The required CT can be achieved through numerous combinations of time and PAA dose. A cost optimization was performed to determine the most effective combination of contact time and dose to reduce overall lifecycle costs while constraining the cost of the contact tank to less than $10 million and ensuring that the resulting residual PAA concentration is between 0.4 mg/L and 1.5 mg/L. Based on these design criteria, a sodium bisulfite system would not be required for any of these set points, although an emergency SBS system is recommended and was included in the lifecycle analysis.

Table ES-1: Required PAA CTs and Design Points

Set Point	Flow (MGD)	Required Log Inactivation	CT*
Average Conditions	90	3.92	87.1
Peak Conditions	170	3.82	74.1
Minimum Conditions	50	2.81	22.4

*CT results include a 1.3x safety factor

Several new collimated beam (CB) analyses were performed to determine if disinfection requirements have changed due to changes in plant influent since 2013. A comparison of the recent and historical CB data performed by Trojan Technologies is shown in **Figure ES-1**. These represent the average of the entire dataset from each year. There is no significant difference between the two datasets. The effectiveness of a UV disinfection system relies heavily on the UV transmittance (UVT) of the influent to the system. During the pilot period, the observed average UVT was 16%, which was lower than those observed during the 2013 pilot testing.

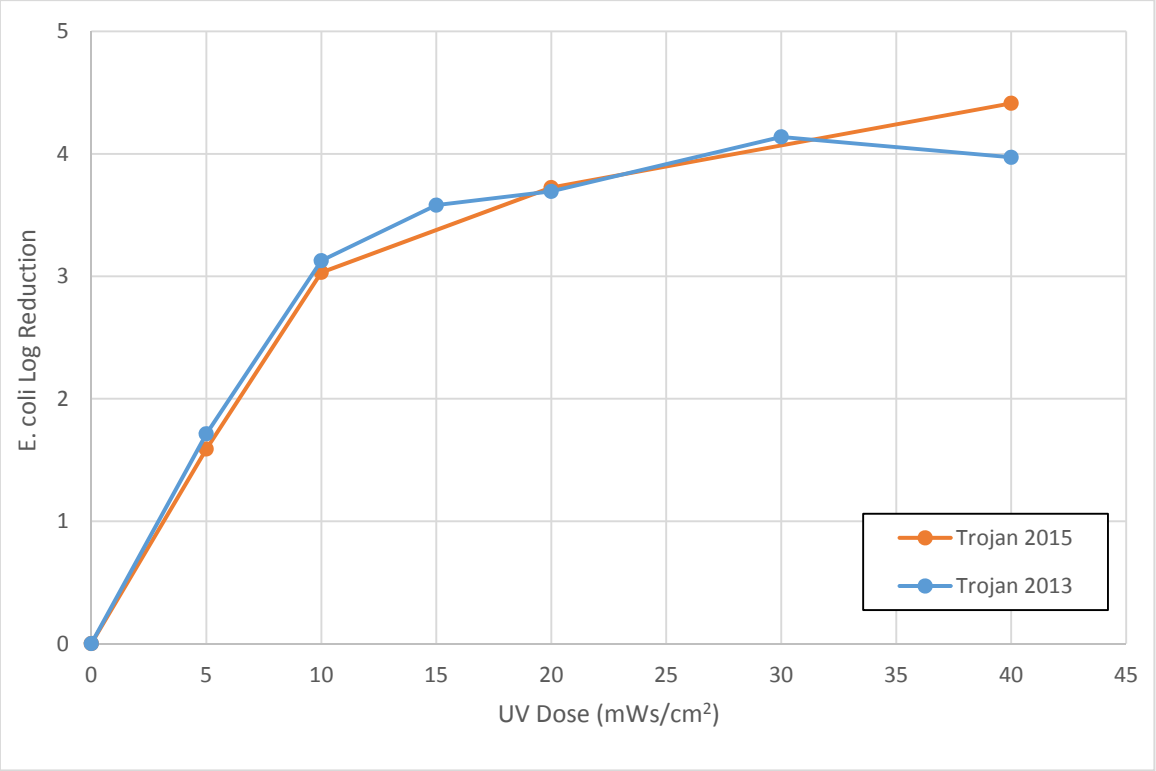


Figure ES-1: Comparison of Recent and Historical Collimated Beam Data

A mechanistic model was developed, based on the results of the combined UV/PAA disinfection bench test, to predict the results of combined disinfection using UV and PAA. Results indicated that the most effective combination of the two is UV followed by PAA. **Figure ES-2** was developed to illustrate the different combinations of UV and PAA that would be required to maintain an effluent concentration of 126 cfu/100 mL of *E. coli.* Although the results are promising, further research is required to accurately describe the effect of combined disinfection, and the economic analysis that was performed based on the results did not indicate significant economic savings through application of a combined disinfection system. The full UV/PAA bench testing report from Trojan Technologies is included as **Appendix A**.

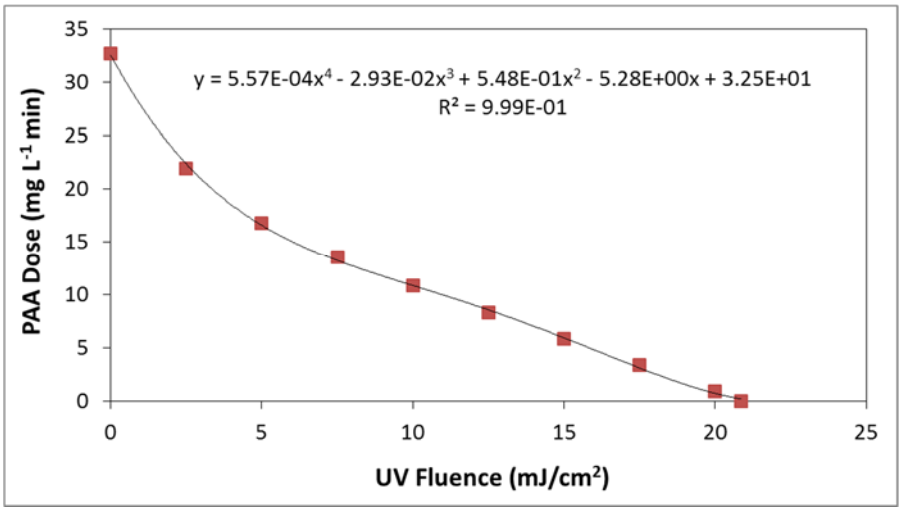


Figure ES-2: Model predicted combinations of PAA dose and UV doses required to achieve an E. coli disinfection target of 126 cfu / 100 mL when applying the sequential UV→PAA treatment process.

Comparative 20 year life cycle costs of three alternative disinfection systems are shown in **Figure ES-3**. The first alternative is a PAA system with a contact tank providing 31 minutes of contact time at average flow, the second system is a PAA system providing 31 minutes of contact team at peak flow, and the third is a UV system designed to treat water at 20% UVT. Providing more contact time at average flow eliminated the need for quenching with sodium bisulfite. Although the lifecycle costs of the UV alternative is lower than that of the two PAA alternatives, the City of Memphis and CDM Smith discussed the impacts caused by the variability of the low UV transmittance seen in the Maxson WWTP effluent. The variability likely stems from the change in processes and raw materials utilized by industrial users within the City's collection system, which may further decrease UVT and adversely affect a UV system. Based upon these discussions it was decided to eliminate UV from the list of disinfection alternatives. Results of the detailed cost analysis and the pilot data indicate that the most cost effective contact tank size to reduce overall lifecycle costs is 489, 000 cubic ft. Design parameters for the PAA system are shown in **Table ES-2**.

Figure ES-3: 20 Year Lifecycle Analysis of Three Disinfection Options

Table ES-2: PAA System Design Parameters

Tank Size = 489, 000 cubic ft				
Set Point	**LI**	**Design CT***	**Contact Time**	**Dose**
		mg/L*min	**min**	**mg/L**
Average Conditions	3.92	87.1	31.0	8.4
Peak Conditions	3.82	74.1	58.5	6.7
Minimum Conditions	2.81	22.4	105.4	4.5

*CT results include a 1.3x safety factor

Section 1
Introduction

1.1 Background

The City of Memphis is comparing the feasibility of installing several different disinfection systems at the T.E. Maxson Wastewater Treatment Plant (Maxson) facility including a standalone PAA system, a UV system, and a combined disinfection system utilizing both UV and PAA. CDM Smith conducted an in depth investigation of all three of these disinfection technologies. The results of the UV investigation and the initial PAA pilot testing have been presented previously, but the results of PAA study presented here. This includes a summary of the on-site pilot testing and the development of the disinfection kinetics model for establishing design criteria for a PAA disinfection system. A summary of the combined UV/PAA testing is also included, and the full report is included as an **Appendix A**.

Historically, PAA has been applied to the food, beverage, medical and pharmaceutical industries; it has been used in Europe at wastewater treatment facilities for over a decade for disinfection. The US Environmental Protection Agency (EPA) has approved three commercially available PAA products for use as a disinfectant to treat wastewater. To date, there are several full-scale facilities that have been permitted with several more under design, and there are a number of pilot studies that have been performed or are ongoing in the United States (US).

1.2 NPDES Permit Requirements

The current NPDES permit, number TN0020729, issued by Tennessee Department of Environment and Conservation (TDEC) authorizes the Maxson WWTP to discharge treated effluent from Outfall 001 to the Mississippi River at Mile 725.0, pursuant to the permit limits and monitoring requirements specified in the permit**.** The facility, as noted in the permit, has a treatment design capacity of 90 million gallons per day (MGD) with a hydraulic capacity of 160 MGD. The effluent limits for parameters relevant to the evaluation of disinfection processes are summarized in **Table 1-1**.

Table 1-1: Disinfection Related Permit Requirements

Parameter	Effluent Discharge
BOD5 or CBOD5	
Monthly average	42 mg/L
Weekly average	63 mg/L
Daily maximum	84 mg/L
pH (s.u.)	6 – 9 s.u.
Total Suspended Solids (mg/L)	
Monthly average	48
Weekly average	72
Daily maximum	96
Turbidity	

Parameter	Effluent Discharge
E. coli	
Monthly average	126 cfu/100 mL
Daily maximum	487 cfu/100 mL
Total Residual Chlorine (or Oxidant)	2.0 mg/L

1.3 Pilot and Bench Study Objectives

In order to develop the disinfection kinetics model for establishing design criteria for a PAA disinfection system, a 30-day side-stream pilot was conducted on site. To determine UV design criteria, samples were taken for collimated beam testing throughout the pilot test period. The goal of this study was to verify previous dose recommendations for effluent discharge to meet permit requirements.

The key pilot study objectives included:

- Refine the design criteria for PAA disinfection to meet disinfection limits
  - Determine the kinetic model parameters to predict PAA disinfection efficacy across a range of doses and contact times
  - Determine the design dose for disinfection set points in conjunction with life cycle cost analysis
- Confirm and update the UV disinfection design dose to support estimates of capital and operating costs

The key bench study objectives included:

- Quantify and compare disinfection kinetics among several UV and PAA combinations including:
  - PAA alone, UV alone, UV followed by PAA, PAA followed by UV, simultaneous disinfection with UV and PAA.
  - Propose a mechanistic model to describe combined disinfection

Section 2

Pilot & Bench Study Procedures

2.1 PAA Pilot Study

The pilot study was designed to evaluate PAA disinfection efficacy across a range of doses, conditions, and contact times to support development a kinetic model to predict PAA disinfection efficacy at different concentrations and contact times. Detailed plans and procedures are contained in the Technical Memorandum entitled Additional Testing for Disinfection – Contract 28231 at the T.E. Maxson Wastewater Treatment Plant, which is located in **Appendix B**. For reference, the PAA dosing schedule is shown in **Table 2-1**, and the sampling matrix is shown in **Table 2-2**. Test methods for each parameter are listed in **Table 2-3**.

Table 2-1: PAA Dose Schedule

Dates	Desired/Target PAA Dose (ppm)
May 4-8, June 2	7
May 11-15, June 3	8
May 18- 22, June 4	9
May 26-28	5
May 29, June 1	6
June 5	10

Table 2-2: Sampling Matrix

Parameter	Influent Control Port	Ports 1-5	Effluent Port 6	Frequency	
Residual PAA (mg/L), field meter	--	--	X	4x/day	4 days/week
		X		1x/day	4 days/week
E. coli (MPN/100 mL), ETC Lab	X	--	X	4x/day	4 days/week
	--	X	--	1x/day	4 days/week
pH (SU) , field meter	X	--	X	4x/day	4 days/week
	--	X	--	1x/day	4 days/week
Temperature (°C), field meter	X	--	--	1x/day	4 days/week
COD (mg/L), ETC Lab	X	--	--	1x/day	4 days/week
Apparent and Filtered Color (PtCo), ETC Lab	X	--	--	1x/day	4 days/week
NO2-N (mg/L), ETC Lab	X	--	--	1x/day	4 days/week
Filtered and Unfiltered UVT (%T), ETC Lab	X	--	--	1x/day	4 days/week
Total Suspended Solids (mg/L), ETC Lab	X	--	--	1x/day	4 days/week

Table 2-3: Test Methods

Parameter	Analysis Method
Residual PAA (mg/L), field meter	EPA, Method 330.5
E. coli (cfu/100 mL)	EPA, 9223B
pH (SU), field meter	ASTM D1293 – 12
Temperature (°C), field meter	SM 2550
Carbonaceous Oxygen Demand (COD) (mg/L), ETC Lab	SM 5220D
Apparent and Filtered Color (PtCo)	SM 2120B
NO2-N (mg/L)	EPA 300.0
Filtered and Unfiltered UVT (%T)	SM 5910B
Total Suspended Solids (mg/L)	SM 2540D

Pilot testing commenced on Monday May 4, 2015 and continued through June 5, 2015. Samples were collected Monday through Thursday during this period. The only exception occurred when weather issues prevented sampling during the fourth experiment on May 20th. **Figure 2-1** highlights some key features of the pilot reactor.

Figure 2-1: Key Features of PAA Pilot Reactor: (Left to Right) Influent Port, Flow Meter, and Sample Port

Samples for *E. coli* were collected in 120 mL jars containing sodium thiosulfate to quench the residual PAA and prevent further bacterial inactivation. Samples collected for COD, TSS, Color, Nitrite, and UVT alkalinity, and ammonia were obtained from the influent port four times per week delivered to the Environmental Testing and Consulting Laboratory in Memphis, TN, for testing. In addition, field tests to measure pH and temperature were conducted each day. Temperature was measured at the influent port once per day, and pH was measured at the influent port and port 6 four times per day.

2.2 Collimated Beam

Nine samples were sent to Trojan Technologies for collimated beam analysis during the pilot period. Samples were irradiated under controlled UV dosing and hydraulic conditions, according to industry defined standards. *E. coli* concentrations were measured at different UV dose intervals to determine the specific dose response characteristic for *E. coli* at Maxson WWTP.

2.3 UV/PAA Bench Study

In order to investigate the feasibility and economics of implementing a combined disinfection technology strategy, bench testing was conducted to inform process selection and sizing. UV/PAA bench testing was conducted at Maxson the week of September 21, 2015. Samples of secondary effluent were collected twice daily (7:00 and 13:00) immediately prior to the discharge from the plant and were treated at bench-scale, on site. In this study, secondary effluent samples were collected and treated with UV doses between 2.5 – 40 mJ/cm^2 and PAA CTs of 2.5 – 50 mg·L^{-1}·min. To evaluate different operational scenarios were evaluated including the following five combinations were applied: PAA alone, UV alone, PAA followed by UV, UV followed by PAA, and simultaneous UV and PAA.

Water quality parameters measured include TSS, COD, UVT, color, and BOD_5. PAA residual was measured using a CHEMetrics PAA vacu-vials test kits and a PAA single analyte meter. The IDEXX Colisure method was used to determine the concentration of viable for E. coli. Sample color was measured at 455 nm using a Hach DR5000 spectrophotometer.

PAA residual concentrations were measured over time, and E. coli samples were collected following PAA measurement. Samples were quenched prior to E. coli enumeration using sodium bisulfite. UV testing was conducted using a collimated beam (CB) apparatus following the IUVA testing protocol; UV irradiation was measured using an International Light Technologies (ILT) ILT1700 radiometer with a UV detector. Samples were irradiated in order to achieve UV doses of 2.5, 5, 10, 15, 20 and 40 mJ/cm^2. Calculations of the unweighted doses at each wavelength band were based on existing protocols developed by Trojan.

For the UV+PAA experiment, effluent was first irradiated to UV doses of 10, 15 or 20 mJ/cm^2, then dosed with PAA as described above. For the PAA+UV experiment, effluent was first dosed with PAA as described above. After set durations, portions of the sample were removed, quenched with a stoichiometric amount of sodium bisulfite, and then subjected to UV doses of 10, 15 or 20 mJ/cm^2. For the simultaneous PAA+UV experiment, two different scenarios were investigated. The first involved dosing PAA at the onset of UV irradiation, irradiating for a set duration, and then removing the sample from UV exposure and continuing to stir until a desired PAA contact time was achieved. The second scenario involved first dosing PAA and allowing it to stir for a period prior to subjecting it to UV irradiation.

Section 3
Data Results and Analysis

3.1 PAA Pilot Study Data Results and Analysis

Standard methods for describing PAA disinfection efficacy are still be developed because the application of PAA as a wastewater disinfectant is relatively recent. CDM Smith has historically applied the Hom's model to disinfection datasets. For PAA, it is thought that the "CT" (residual concentration times contact time) approach that is traditionally used for chlorine disinfection may not be fully adequate to assess the effectiveness of PAA disinfection because of differences in chemical half-lives. In Hom's model, "m" is used to account for the shorter half-life of PAA.

Equation (3-1) $$\log\left(\frac{N}{N_o}\right) = -kC^n t^m$$

Where:

k = the disinfection rate constant otherwise known as the specific coefficient of lethality and depends on the target organism (here, *E. coli*) and other factors such as bacterial association with total suspended solids (TSS)
C = the residual PAA concentration, mg/L
t = contact time, min
Where $n < m$, t (contact time) is the primary factor affecting inactivation and longer contact times will provide additional disinfection benefit
Where $n \sim m$, t (contact time) and PAA residual are similar in their effect on inactivation.
Where $n > m$, chemical residual overrides contact time with respect to disinfection efficacy.
When $m < 1$, there can be a tailing-off behavior at very long contact times.

Data collected during the pilot study were used to determine the Hom's parameters and to model *E. coli* inactivation at different PAA residuals and contact times. A total of 95 test conditions including PAA residual (C), contact time (t), and *E. coli* inactivation (log(N/NO)) were included in the analysis.

The best fit of Hom's model for *E. coli* disinfection was determined using the Excel Solver; results are shown in **Table 3-1**. The correlation between the predicted and the observed bacterial inactivation are shown in **Figure 3-1**. Although the correlation between the model and the measured data is 81%, there does appear to be some over-prediction at low inactivation and under predication at high inactivation.

Table 3-1: Hom's Model Parameters

Hom's Parameters		
k	n	m
0.86	0.18	0.47

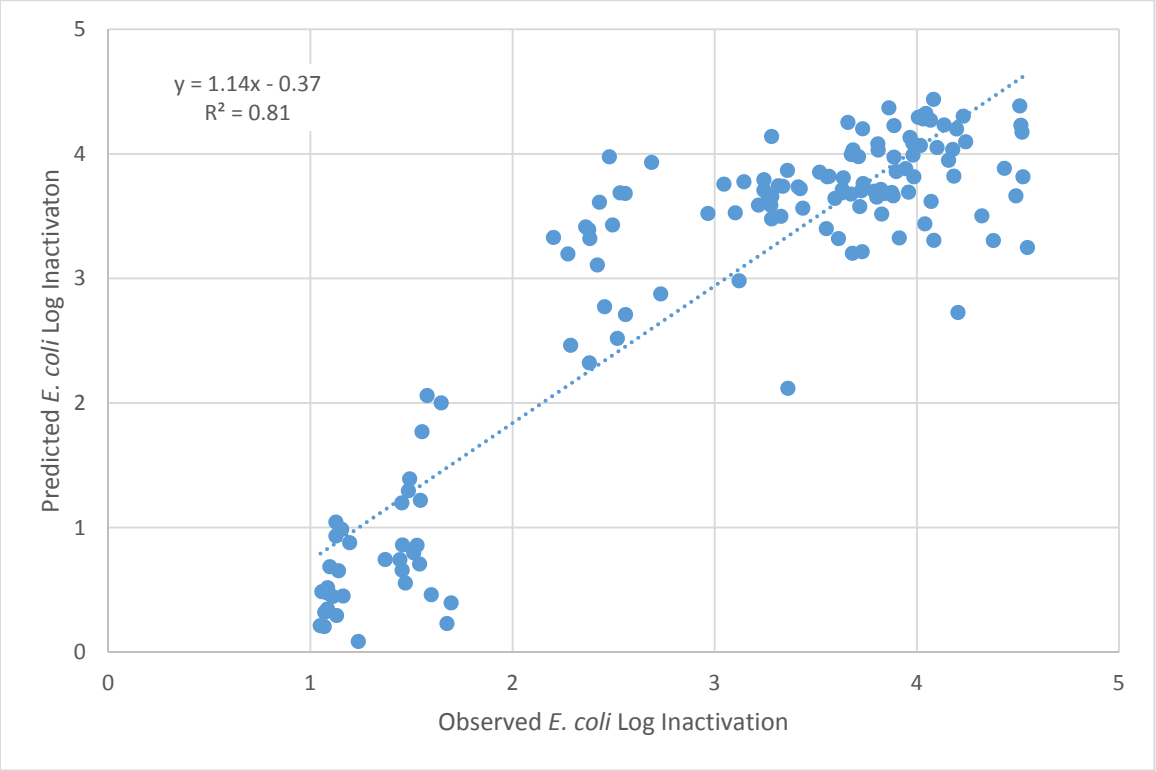


Figure 3-1: Correlation between Measured Log Inactivation and Hom's Model Predicted Inactivation

Because of the spread between the model and the measured data that was observed in the application of Hom's model, the standard CT model was also applied to determine if a better fit could be found. This approach is applied in several steps. In step 1, residual concentration and time are fitted to an exponential decay equation:

Equation (3-2) $$C = (C_0 - D) * e^{-kt}$$

Where:

C = the concentration of PAA at time, t
Co = the applied dose of PAA,
D = the instantaneous demand exerted by the wastewater
k = the specific decay rate of PAA
t = time

Based on this analysis, it was determined that during the pilot period, the average demand exerted by the wastewater was 3.66 mg/L and the specific decay rate was 0.04 per minute. The CT at any time was determined by calculating the integral of the decay equation between 0 and time t.

Equation (3-3) $$CT = \int_0^t (C_o - D) * e^{-kt} = \frac{(C_o - D)}{k} * (1 - e^{-kt})$$

In the next step, the calculated CT from each experiment is correlated to the measured log inactivation. This is shown in **Figure 3-2**. This correlation is slightly stronger and displays less over and under prediction than the Hom's model. However, there is still observable spread between the model and the measured data.

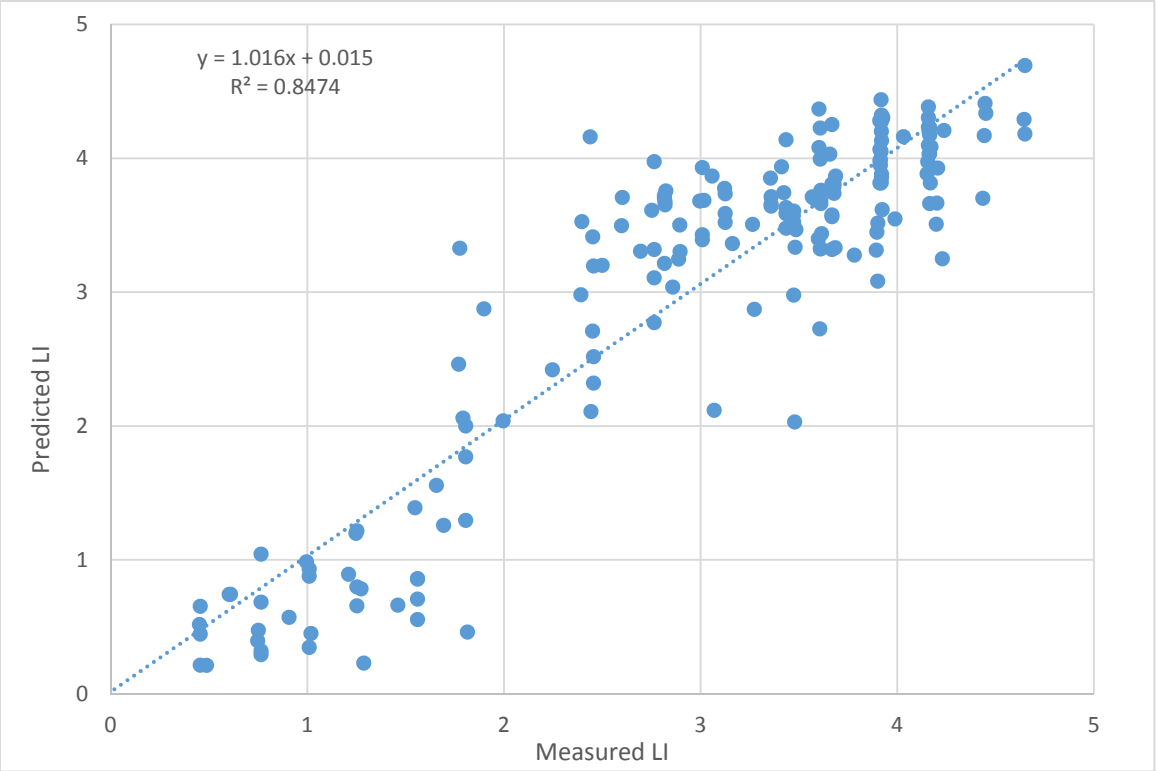


Figure 3-2: Correlation between Measured Log Inactivation and Single Exponential Decay Model Predicted Inactivation

Another predictive model was applied to determine if a stronger correlation could be found. This model also utilizes the integral CT method, but uses a more complex correlation between CT and log inactivation. In this model, the bacterial population is divided into two parts, an easy to inactive portion which represents free floating bacteria, and a hard to inactivate portion, which represents particle associated bacteria. This relationship is descried by the following equation:

Equation (3-4) $$N = N_o * fNd * e^{-k_d * CT} + N_o * fNp * e^{-k_p * CT}$$

Where:

N = the number of viable bacteria, MPN/100 mL
No = the number of bacteria in the wastewater prior to disinfection, MPN/100 mL
fNd = the fraction of the bacterial population that is "easy to inactive"
kd = the specific decay rate of the "easy to inactive" bacteria
fNp = the fraction of the bacterial population that is "hard to inactive"
kd = the specific decay rate of the "hard to inactive" bacteria

The resulting correlation is shown in **Figure 3-3**. The data is best correlated to this model, and the spread between the data and the model is reduced. The PAA dosing recommendations were generated from this model.

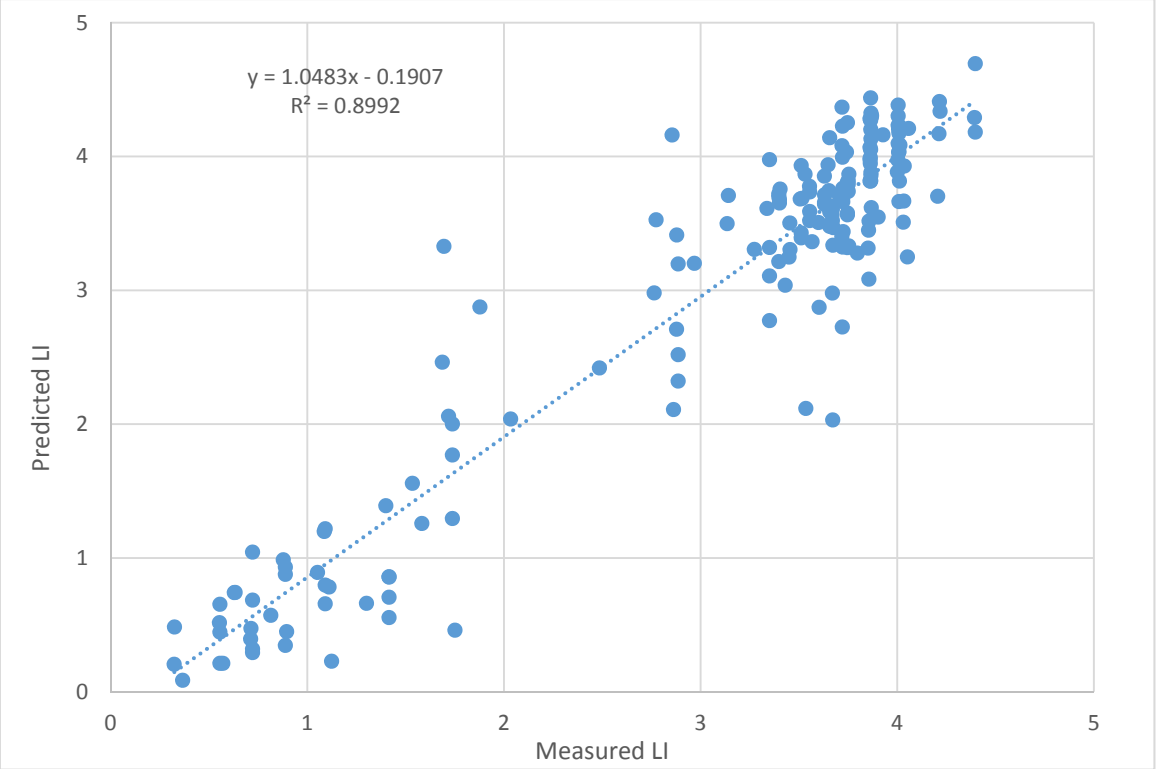


Figure 3-3: Correlation between Measured Log Inactivation and Double Exponential Decay Model Predicted Inactivation

3.2 Collimated Beam Analyses

Several new collimated beam (CB) analyses were performed to determine if disinfection requirements have changed due to changes in plant influent since 2013. A comparison of the recent and historical CB data performed by Trojan Technologies is shown in **Figure 3-4**. These represent the average of the entire dataset from each year. There is no significant difference between the two datasets.

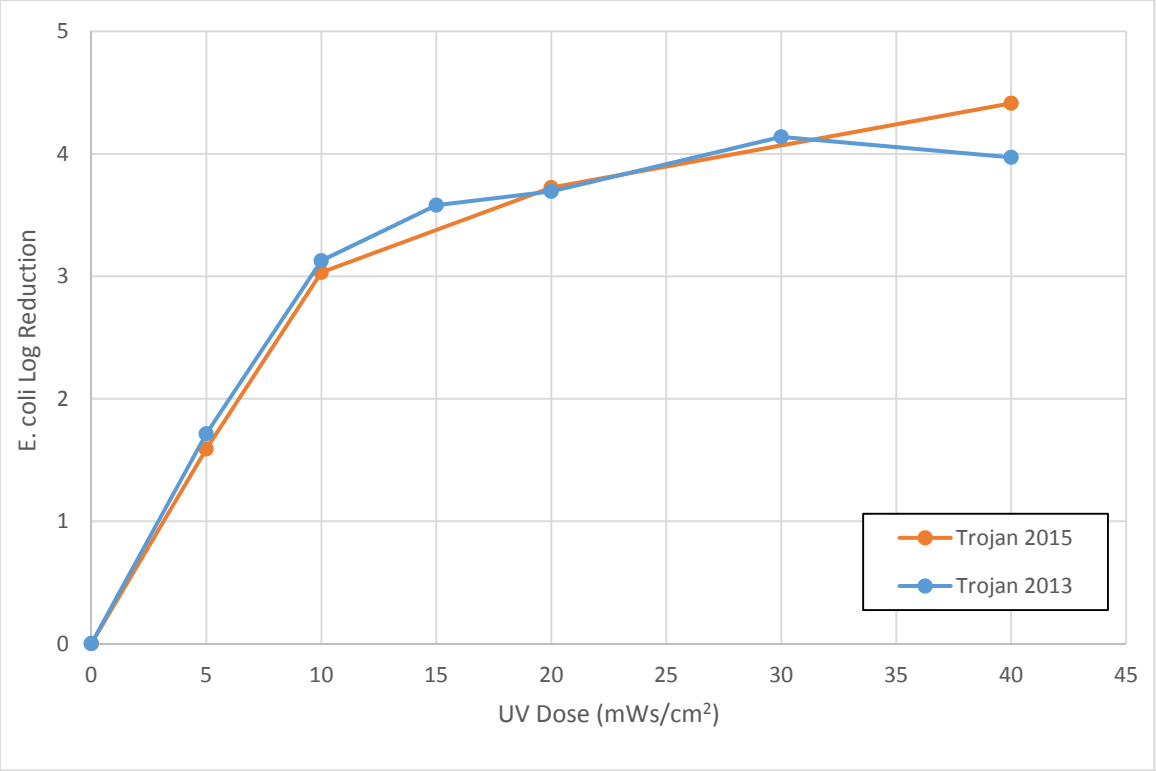


Figure 3-4: Comparison of Recent and Historical Collimated Beam Data

3.3 Combined PAA/UV Disinfection Bench Testing

Data indicated that for combined treatment, the most consistent result and positive results occurred with UV followed by PAA. Based on the analysis of this dataset, a four population mechanistic model to predict both individual and combined disinfection was developed, as described in **Figure 3-5** and Equation 5. In this model, the bacterial population is split into four fractions, each described by a decay coefficient.

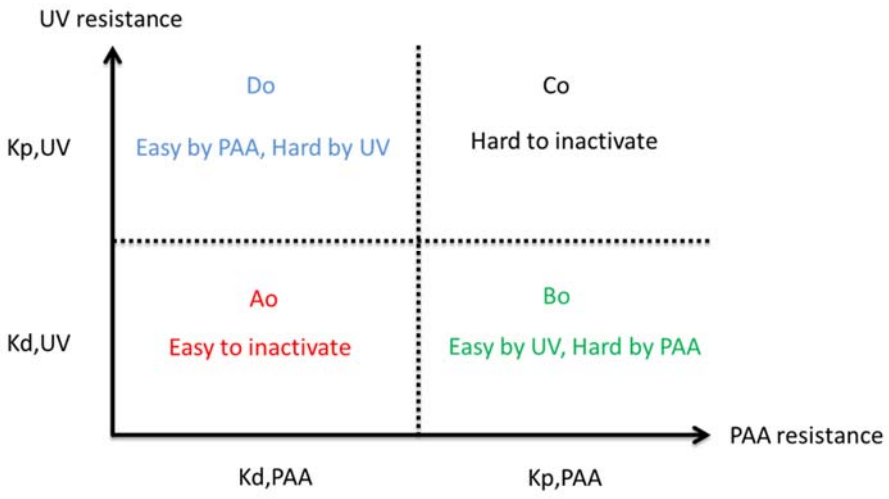


Figure 3-5: Conceptual Description Mechanistic Model to Describe Combined Disinfection

Equation (3-5) $$(N_{total,viable} = A2_{viable} + B2_{viable} + C2_{viable} + D2_{viable}$$

Where:

$N_{total,viable}$ is the total concentration of *E. coli,* after combined disinfection; MPN / 100 mL

$A2_{viable}$ is the concentration of *E. coli* from population A0 after combined disinfection

$B2_{viable}$ is the concentration of *E. coli* from population B0 after combined disinfection

$C2_{viable}$ is the concentration of *E. coli* from population C0 after combined disinfection

$D2_{viable}$ is the concentration of *E. coli* from population D0 after combined disinfection

The model works in two steps. The first step models PAA disinfection (if applicable), and the second set models UV disinfection (if applicable). For example, Equations 6a and 6b are used to calculate the remaining bacteria from the fraction of the population that is easy to kill by both UV and PAA. Similar equations are used to calculate the remaining bacteria from the other populations, and the results are summed to predict the total remaining bacteria in the treated sample.

Equation (6a) $$A_1 = A_o * e^{-k_{d,UV*DOSE}}$$

Equation (6b) $$A_2 = A_1 * e^{-kd,PAA*CT}$$

This model was found to accurately predict both UV alone and PAA alone treatment, as shown in **Figure 3-6**. It was also shown general agreement to data from samples subjected to UV followed by PAA treatment, as shown in **Figure 3-7**.

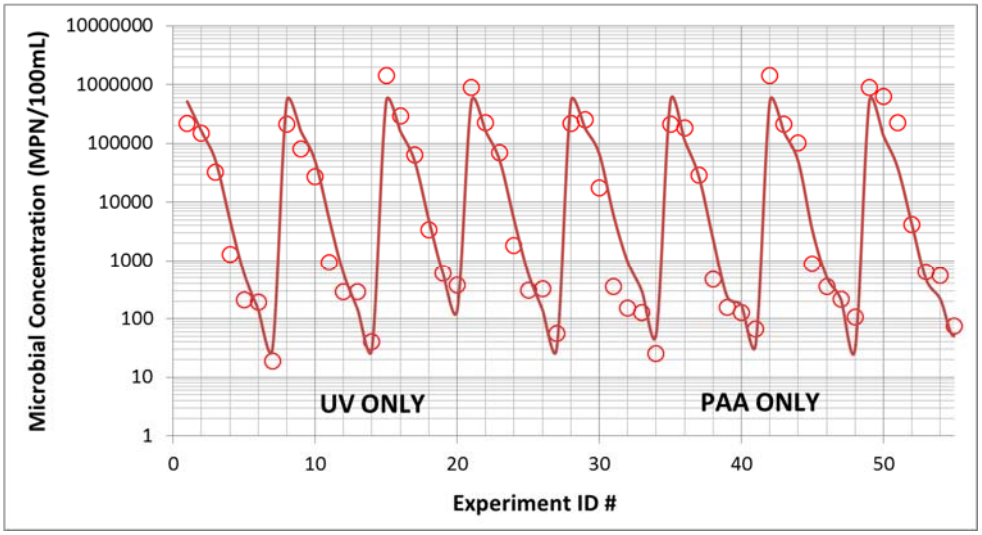


Figure 3-6: Experimental results from inactivation using UV or PAA alone (circles) and predicted values using the mechanistic model.

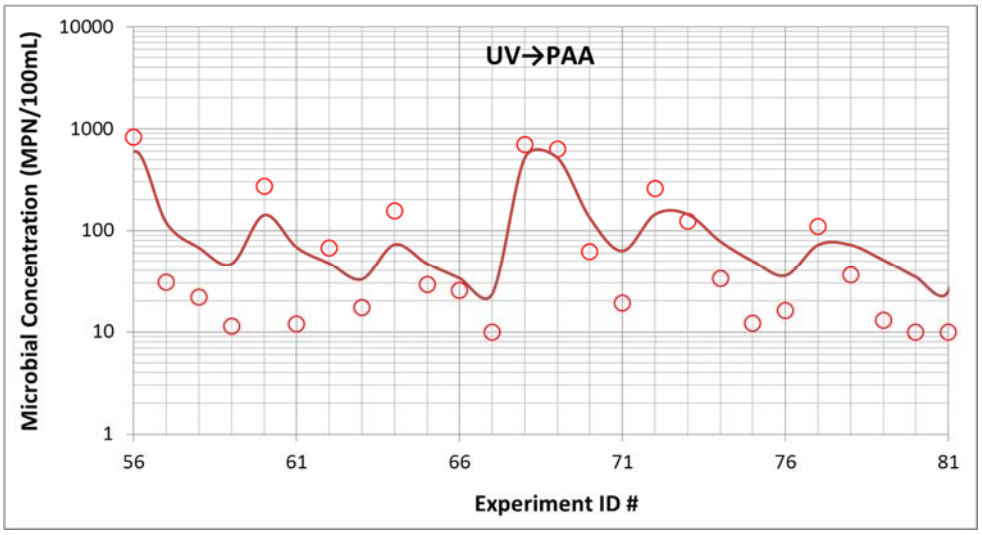


Figure 3-7: Experimental results from inactivation using UV→PAA (circles) and predicted values using mechanistic model.

Based on the mechanistic model, **Figure 3-8** was developed to illustrate the different combinations of UV and PAA that would be required to maintain an effluent concentration of 126 cfu/100 mL of *E. coli*. Although the results are promising, further research is required to accurately describe the effect of combined disinfection, and the economic analysis that was performed based on the results did not indicate significant economic savings through application of a combined disinfection system. The full UV/PAA bench testing report from Trojan Technologies is included as **Appendix A**.

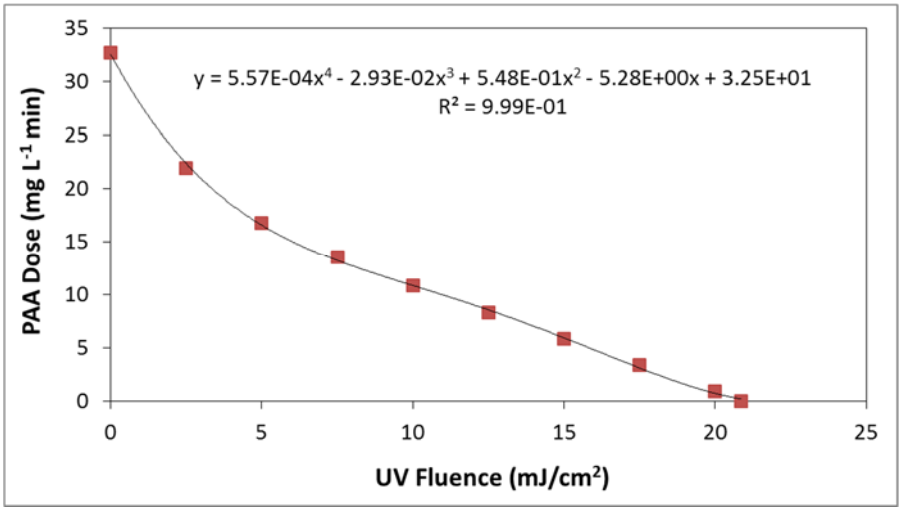


Figure 3-8: Model predicted combinations of PAA dose and UV dose required to achieve a E. coli disinfection target of 126 cfu / 100 mL when applying the sequential UV→PAA treatment process.

Section 4

Conceptual Cost Estimates

The planning level cost estimates developed from the 2013 disinfection alternative testing were revised for the implementation of PAA and UV disinfection systems based on the supplemental pilot results. Costs developed in this preliminary analysis are based on general requirements of each system, including chemical storage requirements, energy costs and auxiliary equipment. These estimates rely on the use of previous estimates and historical data from comparable work, estimating guides, handbooks and costing curves, and are intended for planning purposes and comparing alternatives. For that reason, subtotaled and totaled costs have been rounded to two significant figures. Costs are provided in current (2016) dollars without escalation. The actual cost of any project will depend on actual labor and material costs for competitive bids, project complexity, competitive market condition, actual site conditions, final scope of work, implementation schedule, continuity of personnel and engineering.

It is important to note that in all cases, conservative assumptions regarding equipment redundancy including EPA Class I Reliability guidelines were applied to each system. With more detailed engineering information, the equipment costs and associated contingencies could be reduced. Lifecycle costs were calculated using the following assumptions: project life of 20 years, 4.13 percent interest rate, 3.00 percent inflation rate, and 2.00 percent electric escalation rate above the base inflation rate. The electrical cost rate was estimated at $0.076 per kWh. Maintenance labor costs were estimated at a fully loaded labor rate of $40.00 per hour. The cost of PAA was estimated to be $0.60/lb (delivered).

4.1 UV

The cost of a UV system designed for 35% UVT was estimated during the analysis prepared in 2013, but it is unlikely that it would be adequate based on current water quality conditions, even with improvements made to the secondary treatment process. Therefore, a new cost estimate for a larger UV system designed for 20% UVT was developed with Trojan Technologies. The UV system capital and lifecycle cost breakdown is included in **Appendix C**.

4.2 PAA

4.2.1 PAA Description as Basis of Cost

The PAA disinfection system includes a new contact tank. It is recommended to house chemical feed systems in a protected environment and it has been assumed that a new chemical feed building would be provided. Chemical storage will be provided in tanks located outdoors with appropriate secondary containment; planning level costs have assumed that the storage time for PAA is 14 days. The chemical feed building will be constructed from durable materials that can be easily maintained and will be consistent with the architectural finishes already onsite. This design will meet the hazardous building type criteria for the type and quantity of materials to be stored and the hazardous building type will be designed to meet the required local codes. Personal

safety equipment, emergency showers/eye washes and other necessary equipment will be provided.

A new chemical feed building will be constructed which will contain an electrical room and a mechanical room to house the tepid water skid. The containment areas for chemical feed equipment in the building will be coated to protect the concrete against accidental chemical spills.

A new control system will be put in place to monitor and control the PAA which includes online instrumentation for PAA residual analysis. Signals from the online analyzers will be used to provide automatic control for the PAA and sodium bisulfite feed (if required). All Input/Output (I/O) signals from the disinfection system will be hardwired to a PLC located at the chemical feed building. Additional coordination will be required with the plant staff to provide that the proposed system can be integrated into the existing plant process control system. It is recommended that the City utilize a lease agreement with a PAA supplier, similar to what is being done at the M.C. Stiles WWTP. In this arrangement, the supplier will provide the storage and day tanks, truck unloading and transfer pumps, PAA mixing equipment, on-line PAA analyzers, PAA metering pump skids and all control panels for the entire system.

4.2.2 PAA System Sizing

Required PAA CT was calculated based on three disinfection set points which were determined based on a combined dataset including data measured during the pilot study, data measured during the collimated beam analyses, and data from daily plant operations between 2010 and 2013. Relevant statistic are shown in **Table 4-1**.

Table 4-1 Relevant Influent E. coli Statistics

Statistic	Value
Maximum	5700000
Minimum	13333
Geometric Mean	518730
10 Percentile	152000
20 Percentile	240000
30 Percentile	330778
40 Percentile	455778
50 Percentile	560000
60 Percentile	727000
70 Percentile	926000
80 Percentile	1280000
90 Percentile	1600000

For peak conditions, bacterial concentrations will be reduced from the 90th percentile from the dataset to one half of the daily permit limit of 487 cfu/100 mL. This is equal to a log inactivation of 3.82. For average conditions, the bacterial concentrations will be reduced from the geometric mean from the dataset to one half of the monthly permit limit of 126 cfu/100 mL. This is equal to a log inactivation of 3.92. For minimum conditions, bacterial concentrations will be reduced from the 10th percentile from the dataset to one half of the daily permit limit of 487 cfu/100 mL. This is

equal to a log inactivation of 2.80. The model predicted CT values for these set points are summarized in **Table 4-2**. For conservatism, a safety factor of 1.3 is applied to the CT values for design. This is shown in the CT* column.

Table 4-2 Disinfection Set Points.

Set Point	LI	CT	CT*
Average Conditions	3.92	67	87.1
Peak Conditions	3.82	57	74.1
Minimum Conditions	2.81	17.2	22.4

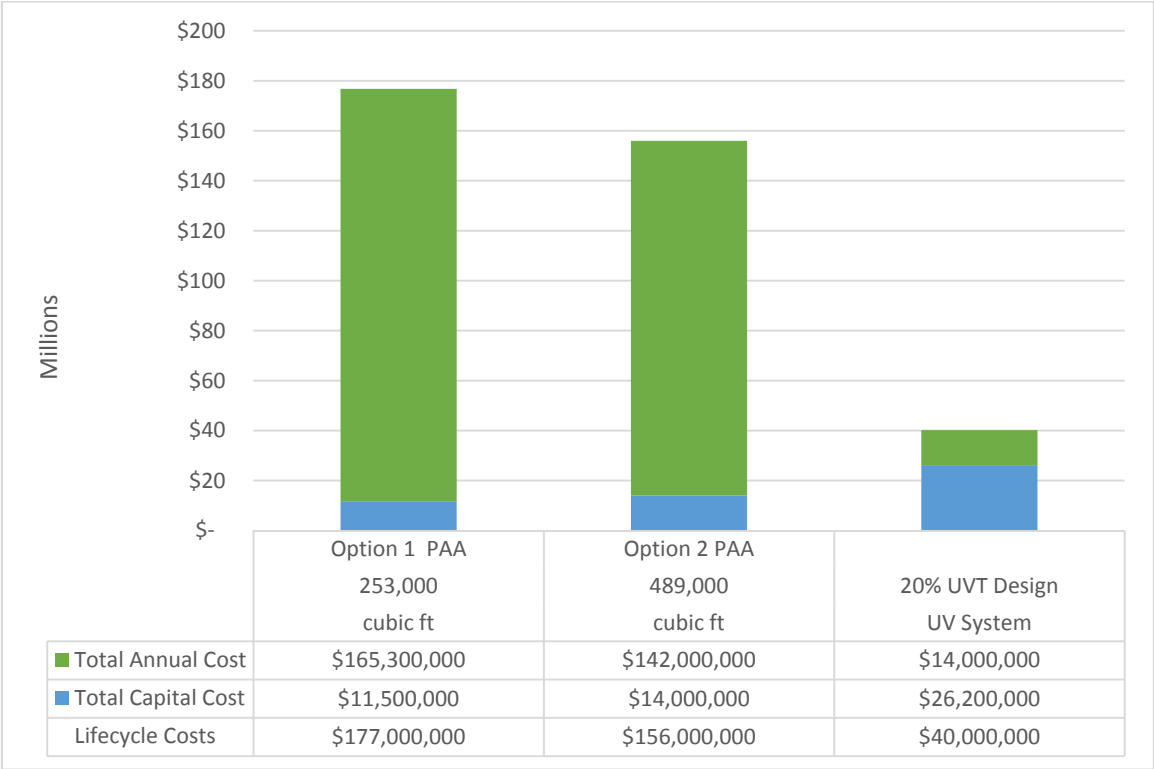
A given CT can be achieved using many combinations of PAA dose and contact time. Lifecycle costs for a PAA system are a function of the contact time at peak flow. The peak flow contact time controls the PAA dose and sodium bisulfite dose (annual costs) at all three design points and the size of the contact tank (capital costs).

Option 1 for the PAA system is based upon a contact tank size in which the contact time at average flow is 30 minutes (16 minutes at peak flow), which is the state mandated minimum. In Option1, a greater PAA dose is required, necessitating a constant sodium bisulfite dose in order to reduce the PAA concentration below the 1.5 mg/L project threshold. This condition was compared to the lifecycle cost for a PAA system in which the contact tank size was optimized to produce the lowest lifecycle cost for a PAA system. The lowest PAA system lifecycle cost occurred when the contact time in the contact tank at peak flow was 31 minutes. At this condition, sodium bisulfite (SBS) is not required. This condition is represented at Option 2. The PAA lifecycle costs are provided in **Appendix C**.

4.3 Cost Summary

Based upon the supplemental testing performed in 2015, the conceptual costs for UV and PAA were revised. Comparative 20 year lifecycle costs for three alternative disinfection systems are illustrated in **Figure 4-1**. The first alternative is a PAA system with a contact tank providing 31 minutes of contact time at average flow, the second is a PAA system providing 31 minutes of contact team at peak flow, and the third is a UV system designed to treat effluent with a 20% UVT. The lifecycle cost estimate performed represents just the disinfection systems and not the rest of the upgrades for the project.

Providing more contact time at average flow for the PAA system eliminated the need for quenching with sodium bisulfite, although the capital costs for a small sodium bisulfite was included for emergency use. Although the lifecycle costs of the UV alternative is lower than that of the two PAA alternatives, the City of Memphis and CDM Smith discussed the impacts caused by the variability of the low UV transmittance seen in the Maxson WWTP effluent. The variability likely stems from the change in processes and raw materials utilized by industrial users within the City's collection system. Based upon these discussions it was decided to eliminate UV from the list of disinfection alternatives. Results of the detailed cost analysis and the supplemental pilot data indicate that the most cost effective contact tank size to reduce overall lifecycle cost is 489,000 cubic ft. As a result, the most cost effective disinfection alternative is PAA - Option 2.



	Option 1 PAA 253,000 cubic ft	Option 2 PAA 489,000 cubic ft	20% UVT Design UV System
Total Annual Cost	$165,300,000	$142,000,000	$14,000,000
Total Capital Cost	$11,500,000	$14,000,000	$26,200,000
Lifecycle Costs	$177,000,000	$156,000,000	$40,000,000

Figure 4-1: Comparative 20 Year Lifecycle Costs

Section 5
Recommendations

Based upon the analysis of the supplemental pilot and bench test results, CDM Smith recommends that PAA be selected as the disinfectant to be utilized at the Maxson WWTP. This recommendation is predicated upon the elimination of UV disinfection because of the influent water quality uncertainty. An economic analysis of combined UV/PAA treatment, based on the additional bench testing, determined that it is not cost effective at this time. Based on the lifecycle analysis of the two PAA options evaluated, it was determined that a 489,000 cubic foot tank providing 31 minutes of contact time at peak flow was the most cost effective design (Option 2) and CDM Smith recommends that the City of Memphis proceed with this design. The associated PAA doses for each disinfection set point are shown in **Table 5-1**. The design elements for this system are described in the conceptual design report (CDR).

Table 5-1 Required PAA Doses to Achieve Disinfection Set Points

	Design CT	Flow	Contact Time	Dose
	mg/L*min	MGD	min	mg/L
Peak Conditions	74.10	170	31	8.36
Average Conditions	87.10	90	59	6.73
Minimum Conditions	22.36	50	105	4.50

Appendix A

Evaluating UV and PAA disinfection strategies for T.E. Maxson Wastewater Treatment Plant

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Evaluating UV and PAA disinfection strategies for T.E. Maxson Wastewater Treatment Plant

Final version – January 21, 2016

Experiments performed by: Adrian Murray, Wenjun Sun, Joshua Goldman

Report prepared by: Adrian Murray, Siva Sarathy

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Report Submitted to: Brian Hilts, Josh Goldman, Kati Bell

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Contents

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1 DISCLAIMER

This report provides a description of experimental work performed by Trojan Technologies on the disinfection of *E. coli* in secondary settled wastewater obtained from the T.E. Maxson Wastewater Treatment Plant (WWTP) in the City of Memphis (City), Tennessee. It also provides an analysis of data collected from bench-testing of UV and PAA, individually and in combination. While disinfection system sizing and economic evaluations are performed and presented in this report, they do not constitute Trojan's final recommendation on disinfection system sizing and costs.

2 CONFIDENTIALITY

The data, methodologies, data analyses concepts, and discussions are property of Trojan Technologies and should be treated with confidentiality as stipulated by existing Non-Disclosure Agreements between Trojan Technologies and CDM Smith.

3 INTRODUCTION

The Maxson WWTP is located in the southwestern portion of Memphis, Tennessee at 2685 Steam Plant Road. The facility, over the last five years, has treated an average of 72 million gallons per day (MGD) but is currently treating an average of just less than 70 MGD, due to the closing of the Cargill wet corn milling facility. The Maxson WWTP has served the City since its commissioning in 1975. The current liquid treatment process consists of coarse bar screens, grit removal, recently installed fine bar screens, primary clarification, high-rate biotowers, activated sludge and secondary clarification. Biosolids treatment consists of anaerobic digestion and dewatering with the final disposition of solids being land application and a surface disposal site as shown in Figure 1.

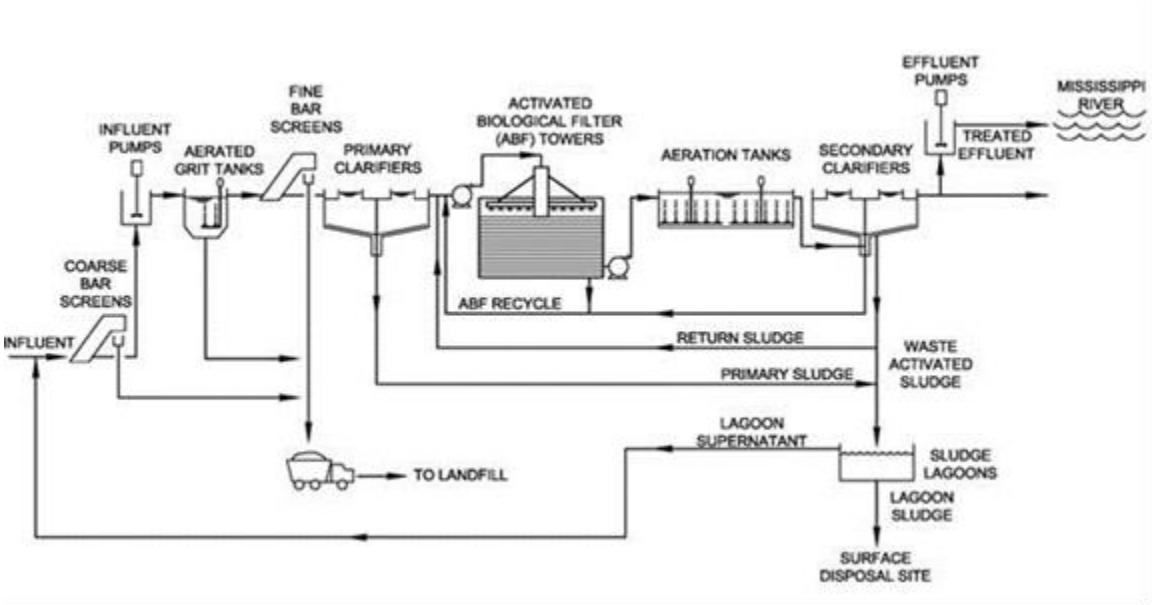

Figure 1: Process flow diagram for the Maxson WWTP.

The facility is currently evaluating the plant processes to determine what changes will be required to meet discharge permit requirements at the design flow of 90 MGD. Proposed changes include expanding the activated sludge process and removing the high-rate biotowers from the flow treatment stream. In addition, the City is planning to provide a new disinfection process. The two methods of disinfection being evaluated are ultraviolet irradiation (UV) and chemical oxidation using peracetic acid (PAA).

UV disinfection is employed throughout the drinking and wastewater treatment industry due to its efficacy for inactivating human pathogens, as well as providing a relatively low lifecycle cost in a small footprint. Inactivation of a pathogen or indicator microorganism occurs when photons of UV light are absorbed and cause damage to an organism's deoxyribonucleic acid (DNA) or ribonucleic acid (RNA), preventing reproduction.

Peroxyacids are a class of chemical disinfectants gaining attention due to the high efficacy at inactivating organisms, low undesirable byproduct formation, and rapid decay in the environment. Peracetic acid is a strong oxidant with a biocidal mode of action via cell membrane damage. Hydroxyl radicals (·OH) and reactive oxygen species released during decomposition reactions are believed to be secondary modes of action (Lubello et al., 2002). Peroxyacids, such as PAA, may also play a role in the disruption of the chemisomotic function of the lipoprotein cyctoplasmic membrane (Santoro et al., 2007, Baldry et al., 1989, Leaper, 1984).

Researchers have reported on the potential benefits of combining of UV and PAA to enhance the disinfection of municipal wastewater (Rajala-Mustonen et al. 1997, Caretti & Lubello 2003, Lubello et al. 2004, Heinonen-Tanksi 2005, Koivunen & Martin & Gehr 2007, Budde & Vineyard 2010, Gonzalez et al. 2012, Block & Tran 2015). However, the exact mechanism for this enhancement is not clear, and there is no general consensus on the mechanisms of disinfection that govern the application of a combined UV and PAA process. It is generally reported that the addition of PAA prior to UV irradiation increases inactivation through an advanced oxidation process (AOP), resulting from the photolysis of the O–O bond in the PAA molecule, generating a hydroxyl radical (·OH) (Caretti and Lubello 2003, Lubello et al. 2002). While investigating the combination of UV and PAA, Lubello et al. (2002) found a PAA concentration between 2 and 8 mg/L or a UV fluence of 120 to 300 mJ/cm^2 were unable to reach the target disinfection levels; however, when a PAA concentration of 2 mg/L was applied immediately before a UV fluence of 192 mJ/cm^2, over 4-log inactivation of total coliform was achieved. However, Gonzalez et al. (2012) reported that when peracetic acid and ultraviolet irradiation were combined, at a low UV fluence (13 mJ/cm^2), there was no synergistic benefit observed, when PAA was added either before or after UV irradiation.

There are other possible synergies between PAA and UV that have not yet been investigated. The addition of PAA to wastewater may increase the UVT% (percent UV transmittance) through oxidation of organic compounds. This would decrease the required UV fluence to reach a target log inactivation of bacteria. PAA may also reduce the concentration of solids which may shield bacteria from UV irradiation. The obvious non-synergistic effect of PAA addition prior to UV is that the bacterial load entering the UV system is reduced. However, none of these effects have been quantified. There is still considerable ambiguity in the current understanding of the mechanisms of UV and PAA treatments.

In this study, the sequential and simultaneous use of UV and PAA disinfectants was investigated. The effluent at the Maxson WWTP is anticipated to be a good candidate for this combination treatment because of its low UVT, high initial *Escherichia coli* (*E. coli*) concentrations (10^5 – 10^6 most probable number (MPN)/100 mL), and high and variable PAA demand and decay. The use of these two processes together may lead to substantial savings by leveraging two disinfection mechanisms (DNA-based for UV and cell membrane-based for PAA) that may also have synergistic effects.

4 MATERIALS AND METHODS

To investigate the feasibility and economics of implementing a combined disinfection technology strategy, bench testing was conducted to inform process selection and sizing. Samples of secondary effluent were collected twice daily (7:00 and 13:00) immediately prior to the discharge from the plant and were treated at bench-scale, on site. Different operational scenarios were evaluated including the following five combinations: PAA alone, UV alone, PAA followed by UV, UV followed by PAA, and simultaneous UV and PAA.

4.1 Analytical Methods

Table 1 provides a summary of the parameters measures and analytical methods employed for the bench-scale treatability study.

Table 1: Summary of analytical methods used.

Parameter	Analytical Method	Instrument
TSS	Standard Method 2504	n/a
COD	Standard Method 5220	n/a
UVT	Standard Method 5910	Hach DR500 at 254 nm
Color	Standard Method 2120	Hach DR500 at 455 nm
BOD5	Standard Method 5210	n/a
PAA concentration	DPD method	CHEMetrics vacu-vials and Single-Analyte-Photometer
E. coli concentration	Standard Method 9223	IDEXX Colisure*

*Although the discharge permit specifies bacterial concentration in colony forming unit (cfu), the EPA approved IDEXX Colisure method, which measures bacterial concentration in most probable number (MPN) was used in the study.

4.2 Bench Test Protocols

In this study, secondary effluent samples were collected and treated with PAA to achieve residual concentration*contact time (CTs) of 2.5 – 50 mg·min/L. PAA tests were conducted in clean glass beakers (500 or 2000 mL), and mixed continuously using a magnetic stirrer (600 rpm). Measurements of PAA residuals were collected over time, and *E. coli* samples were collected following PAA quenching using sodium bisulfite. The four samples collected between September 22 – 24 were each treated with PAA (C_O = 5.0 mg/L) in order to estimate the demand/decay for each sample. These results were then used to estimate the contact times needed to achieve CT doses ranging from 2.5 – 50 mg·min/L for each sample. The demand/decay kinetic parameters were recalculated using the experimental results from each inactivation experiment.

UV testing was conducted using a collimated beam (CB) apparatus, illustrated in Figure 2. UV irradiation was measured using an International Light Technologies (ILT) ILT1700 radiometer with a UV detector calibrated at 253.7 nm (monochromatic output of low-pressure mercury amalgam lamp). Samples were irradiated in order to achieve UV fluences of 2.5, 5, 10, 15, 20 and 40 mJ/cm^2. Calculations of the fluence were based on standardized method for fluence determination presented by Bolton & Linden (2003).

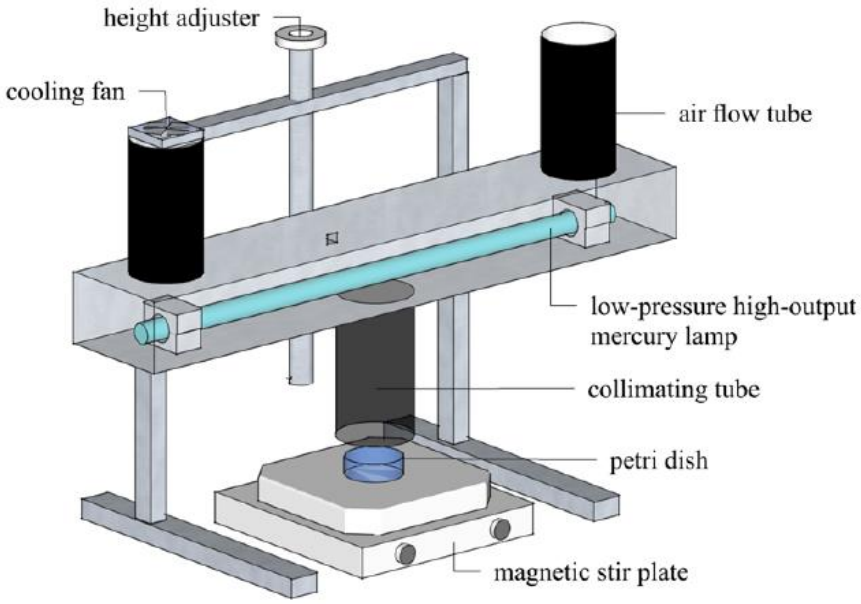

Figure 2: Collimated beam apparatus employed for bench-scale UV testing.

For the UV+PAA experiment, effluent was first irradiated to UV fluences of 10, 15 or 20 mJ/cm^2, then dosed with PAA as described above. For the PAA+UV experiment, effluent was first dosed with PAA as described above. After set durations, portions of the sample were removed, PAA quenched with sodium bisulfite, and then subjected to UV fluences of 10, 15 or 20 mJ/cm^2. For the simultaneous

PAA+UV experiment, two different scenarios were investigated. The first involved dosing PAA at the onset of UV irradiation, irradiating for a set duration, and then removing the sample from UV exposure and continuing to stir until a desired PAA contact time was achieved. The second scenario involved first dosing PAA and allowing it to stir for a period prior to subjecting it to UV irradiation.

The full test plan and experimental matrix is included in Appendix A.

4.3 Data Analyses

4.3.1 PAA Decomposition Kinetics

PAA residuals were fitted to a demand/decay curve using Equation 1. The PAA CT (mg·min/L) was determined by integrating the area under the demand/decay curve and is calculated using Equation 2. An example is shown in Figure 3.

$$C = (C_0 - D)e^{-kt} \quad \text{[Equation 1]}$$

Where,

C is the concentration of PAA (mg/L) at time t (min)

C_0 is initial concentration of PAA (mg/L)

D is the instantaneous demand of PAA (mg/L)

k is the decay rate constant of PAA (1/min)

t is the contact time (min)

$$CT = \frac{C_0 - D}{k}(1 - e^{-kt}) \quad \text{[Equation 2]}$$

Where,

CT is the integral PAA dose (concentration * contact time); mg·min/L (Santoro et al., 2015)

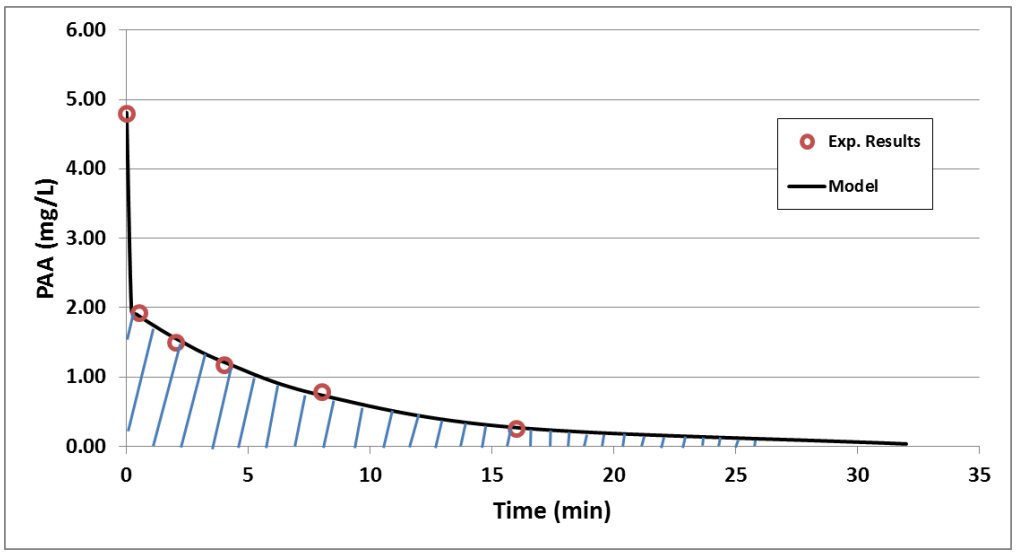

Figure 3: PAA demand/decay curve (black) generated from experimental data using Equation 1. The PAA CT (mg·min/L) is represented as the area under the curve (blue hatchmarks), and is calculated using Equation 2.

4.3.2 PAA and UV Disinfection Kinetics

The models that are used for disinfection for PAA and UV disinfection when used individually are well known such as the Chick-Watson model and the Hom's model. PAA disinfection can be evaluated as a function of residual and contact time. The disinfection kinetics of microorganisms is conventionally modelled by relating the extent of inactivation of the microorganisms to the products of the disinfectant dose and the contact time. For the PAA process the product of dose and contact time is the defined as the CT (mg·min/L) while for UV the product of dose and contact time is the UV fluence (mW*sec/cm^2). That said, there is no published model for evaluating a combined PAA and UV disinfection process and the development of such a model is provided herein.

To develop an disinfection kinetic model, the concentration of viable for *E. coli* can be plotted against either PAA – CT dose or UV fluence and the data fitted using the double exponential inactivation model, described in Equation 3.

$$N = N_d e^{-k_d DOSE^m} + N_p e^{-k_p DOSE} \qquad \text{[Equation 3]}$$

Where,

N is the total concentration of viable *E. coli*; MPN / 100 mL

N_d is the concentration of particle-associated *E. coli*; MPN / 100 mL

N_p is the concentration of dispersed *E. coli*; MPN / 100 mL

k_d is the first order inactivation rate constant for particle-associated *E. coli;* for PAA = L/ mg·min, for UV = cm^2/mJ

k_p is the first order inactivation rate constant for dispersed *E. coli*; for PAA = L/ mg·min, for UV = cm^2/mJ

m is an inactivation kinetic model parameter describing shoulder effects (*m* = 1 for with UV doses)

DOSE is the dose; for PAA = mg·min/L, for UV = mJ/cm^2

5 RESULTS AND DISCUSSION

The results and discussion are presented in below in five sections: (1) water quality testing (Section 5.1), (2) PAA disinfection testing (Section 5.2), (3) UV disinfection testing (Section 5.3), (4) combined UV and PAA disinfection testing, and (5) modelling the disinfection kinetics of the sequential UV→PAA process. Each section presented results from the experiments conducted as well as sizing calculations for the UV and PAA disinfection processes to meet the plant's disinfection targets.

5.1 General Water Quality

Each of the four samples collected over the 2 day period was analyzed for UVT, color, TSS, COD and BOD. The results of these tests are summarized in Table 2. The water quality was fairly consistent among the samples and was not affected by the flow rate in the plant.

Table 2: Maxson secondary effluent water quality.

Sample ID	Plant Flow (mgd)	UVT (%)	Color (PtCo)	TSS (mg/L)	COD (mg/L)	BOD (mg/L)
Sept. 22 – AM	60.6	19.5	175	16	115	20
Sept. 22 – PM	56.7	20.8	160	14	111	16
Sept. 24 – AM	62.5	20.2	188	16	114	20
Sept. 24 – PM	109.5	20.1	169	17	109	16

5.2 PAA Disinfection Tests

There are several different commercial formulations of PAA available, with differing concentrations of PAA and hydrogen peroxide. For this study, a 22 wt% solution of PAA was used for testing. To provide that this formulation of PAA would be suitable for use, it was compared with a 15 wt% PAA formula, which has been previously investigated at the Maxson WWTP. The demand/decay kinetics, as well as microbial inactivation were investigated, and the results are summarized in Table 3 and Figure 4.

Table 3: PAA demand/decay (D, *k*) for 15 wt% and 22 wt% PAA solutions.

Sample ID	Demand (D, mg/L)	Decay (*k*, 1/min)
PAA 15 wt%	2.81	0.125
PAA 22 wt%	2.55	0.096

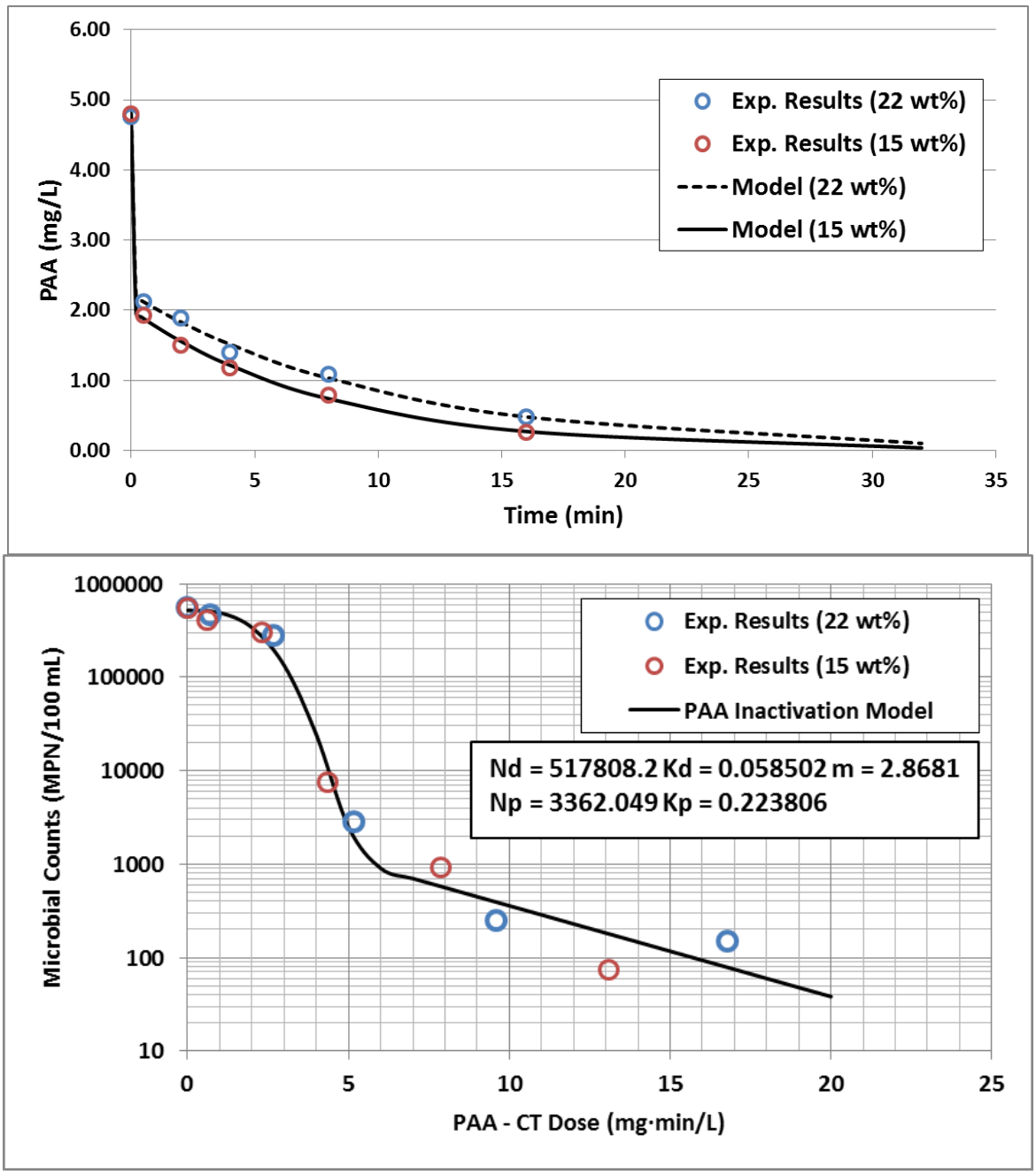

Figure 4: PAA demand/decay for 22% and 15% PAA solutions added to Maxson SE at C_O = 5 mg/L (Top) Data modeled (black lines) from experimental results using Equation 1. Microbial inactivation of Maxson SE treated with 22% and 15% PAA solutions at a C_O = 5 mg/L (Bottom).

There was minimal difference in the demand/decay kinetics when using either 22% or 15% PAA solutions. There was a slightly higher initial demand and decay using the 15% PAA solution, however the difference was minimal. Both the 22% and 15% PAA solutions displayed the same microbial inactivation kinetics, as microbial inactivation plotted against CT dose show the two inactivation curves essentially overlap.

Four samples collected between September 22 – 24 were each treated with PAA in order to achieve CT doses ranged from 2.5 – 50 mg·min/L. The PAA demand/decay results are summarized in Table 4 and Figure 5. Samples collected in the morning had higher PAA demand (ca. 3.5 mg/L) than samples collected in the afternoon (ca. 2.75 mg/L). This is line with the slightly higher BOD_5 measured in those samples. All samples had similar decay rates (ca. 0.060 1/min)..

Table 4: PAA demand/decay parameters (D, *k*) for PAA only disinfection.

Sample ID	Demand (D, mg/L)	Decay (*k*, 1/min)
Sept. 22 – AM	3.58	0.063
Sept. 22 – PM	2.60	0.057
Sept. 24 – AM	3.50	0.056
Sept. 24 – PM	2.91	0.058

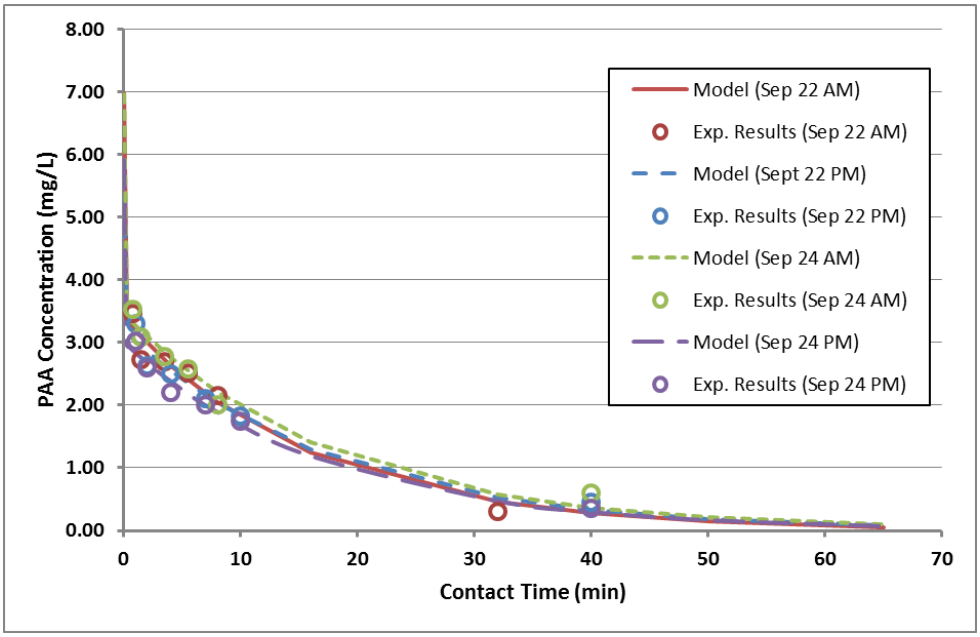

Figure5: PAA demand/decay model plots for Samples collected Sept 22 and Sept 24 (model curves generated from experimental results using Equation 1).

The *E. coli* inactivation kinetics by PAA was calculated for each sample by plotting the viable concentration of *E. coli* on a log scale (y-axis) against the PAA – CT dose (x-axis), and is shown in Figure 6. Two different models were generated from the data. The first inactivation curve (Figure 6 - top) was generated from the all data collected during September 2015. This model was used to predict the CT dose required to meet the plant's disinfection target of 63 MPN / 100 mL (half the 30-day geomean disinfection permit of 126 MPN / 100 mL); CT = 49.2 mg·min/L. The second curve (Figure 6 – bottom) was generated using only samples in which the least amount of inactivation was observed per CT dose. In other words, by selecting data corresponding to the maximum MPN at each CT dose applied, a plot of the most challenging inactivation conditions could be generated. This data was then used to estimate the plant's disinfection target of 244 MPN / 100 mL (half the daily maximum disinfection permit of 487 MPN / 100 mL); CT = 36.0 mg·min/L. Based on these results, it is recommended that a PAA CT dose of ≥ 49.2 mg·min/L be applied in order to meet the plant's disinfection targets.

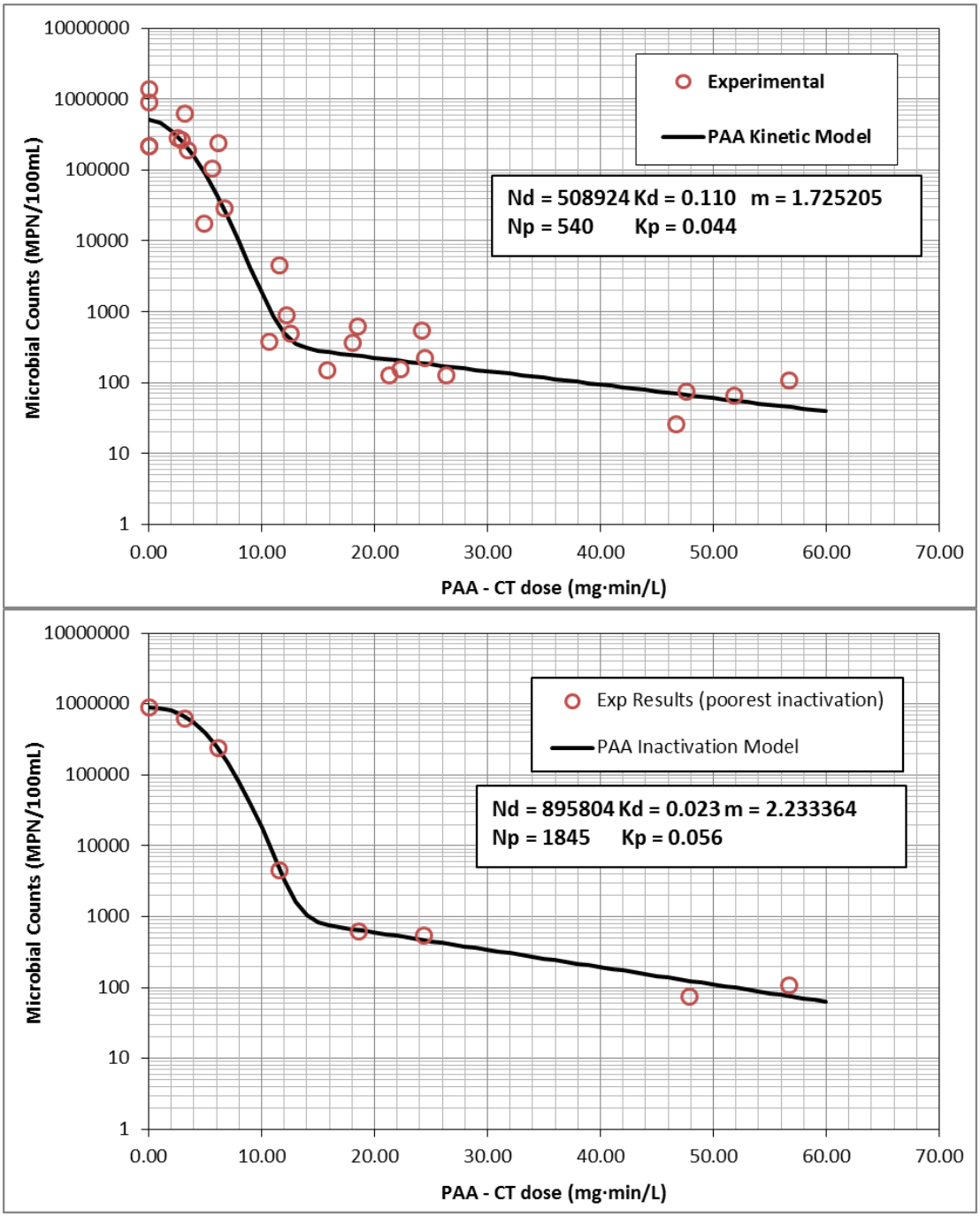

Figure 6: The inactivation of *E. coli* using PAA for Maxson SE samples collected Sept. 22 and Sept. 24 (Top). Inactivation curve for poorest inactivation levels measured on Sept. 22 and Sept. 24 (Bottom).

5.3 UV Disinfection Tests

Collimated beam tests were performed to determine the inactivation of *E. coli* by UV irradiation and to determine the UV fluence for sizing a UV system. Over the last 3 years, Trojan has performed 22 collimated beam tests on multiple samples obtained from the Maxson facility. Water quality ranges from 7 - 34% UVT and 14 - 113 mg/L TSS. To provide a robust and representative sizing of the UV disinfection system, all data from the 22 collimated beams tests have been considered in this analysis.

Figure 7 illustrates data from all the UV collimated beam tests (left) and data representing the poorest inactivation rates (right). Using data in Figure 7 - top, a minimum UV fluence of 20.1 mJ/cm^2 was required to achieve a target of 63 MPN / 100 mL (half the 30-day geomean disinfection permit of 126 MPN / 100 mL). The second curve (Figure 7 – bottom) was generated using only samples in which the least amount of inactivation was observed per UV fluence delivered. In other words, the data was segregated by selecting the maximum MPN at each UV fluence applied thereby providing a plot of the most challenging inactivation conditions. This data was then used to calculate that a minimum UV fluence of 19.2 mJ/cm^2 was required to achieve a target of 244 MPN / 100 mL (half the daily maximum disinfection permit of 487 MPN / 100 mL).

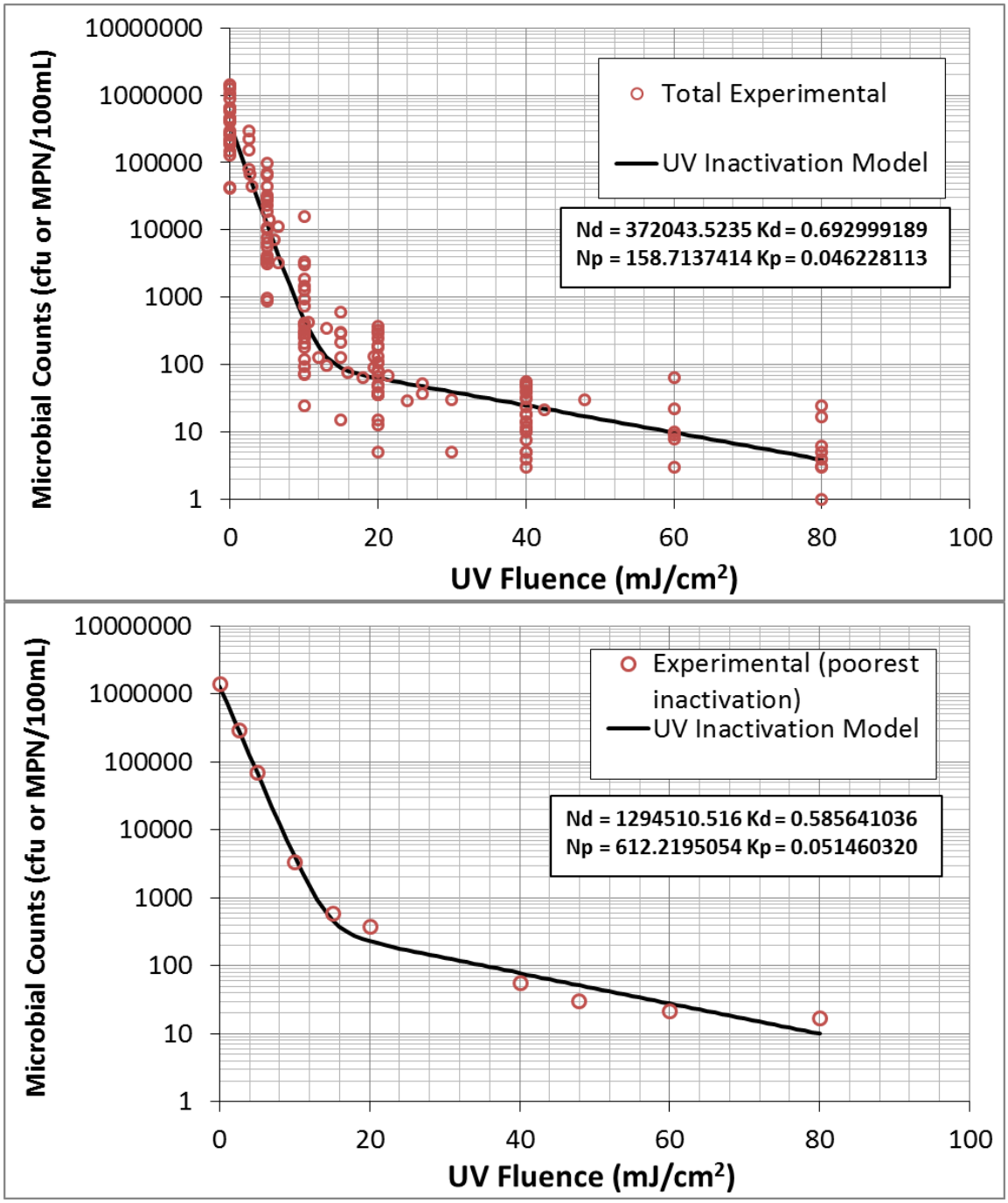

Figure 7: Inactivation of *E. coli* using UV for Maxson SE samples collected 2013 and 2015. Inactivation curves for all data points (top) and poorest inactivation levels (bottom).

5.4 Combined UV and PAA Disinfection Tests

Three distinct scenarios were performed with respect to testing the combined UV and PAA disinfection processes: UV prior to PAA (UV→PAA), PAA prior to UV (PAA→UV), simultaneous UV and PAA (UV+PAA). For the UV→PAA tests, UV fluences of 10, 15, and 20 mJ/cm^2 were applied prior to PAA addition, and PAA CTs ranged from 5-25 mg·min/L. Figures 8 – 10 illustrates the results for viable *E. coli* as a function of PAA CT exposure with different levels of UV fluence applied, prior to PAA treatment.

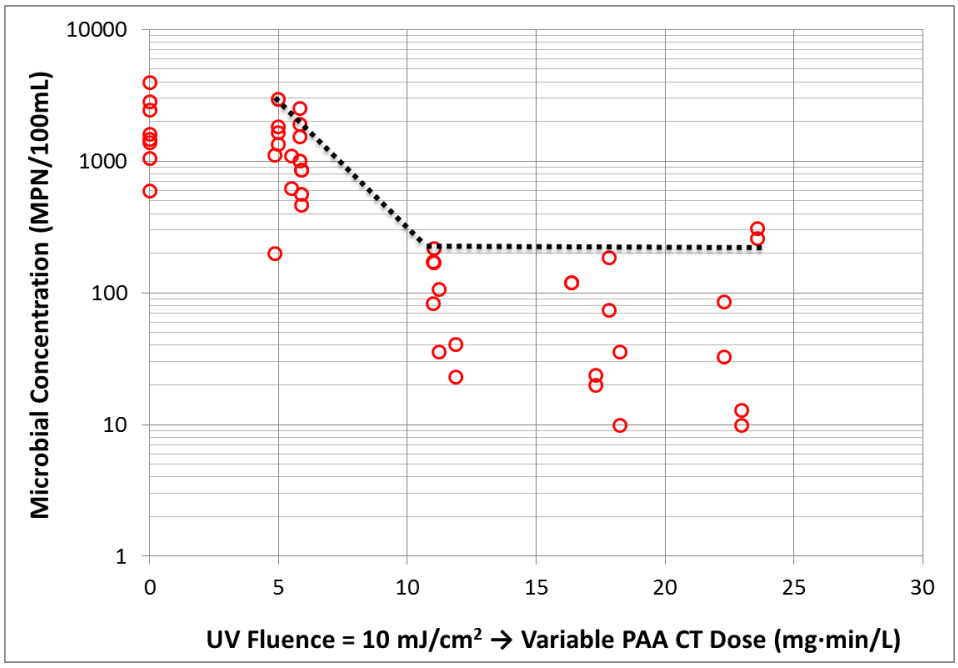

Figure 8: Inactivation of *E. coli* for UV→PAA treatment scenario where PAA treatment is preceded by a UV fluence of 10 mJ/cm^2. Dotted lines are illustrative to show general trend.

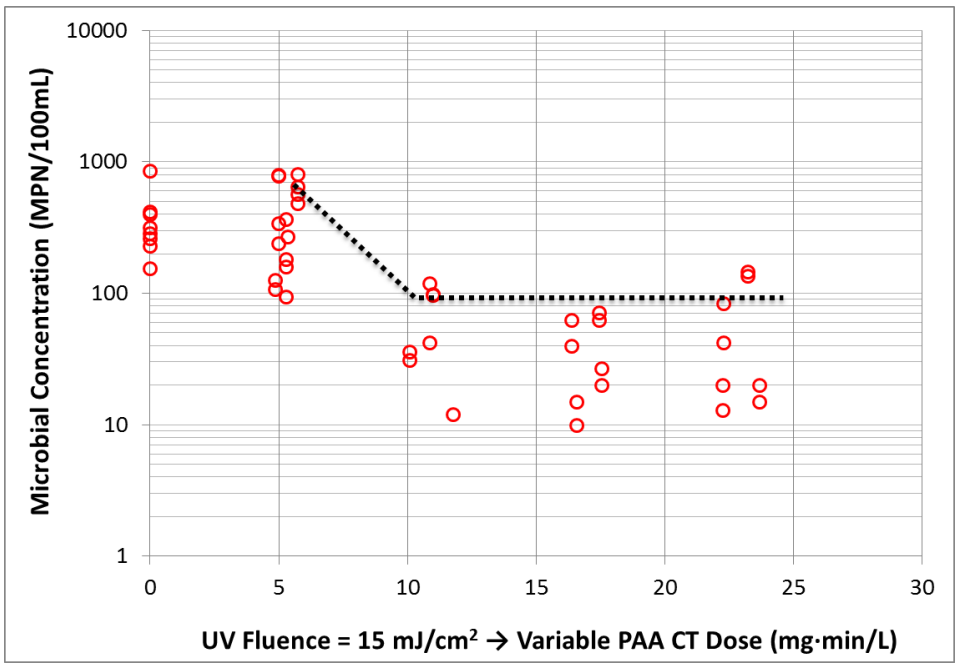

Figure 9: Inactivation of *E. coli* for UV→PAA treatment scenario where PAA treatment is preceded by a UV fluence of 15 mJ/cm^2. Dotted lines are illustrative to show general trend.

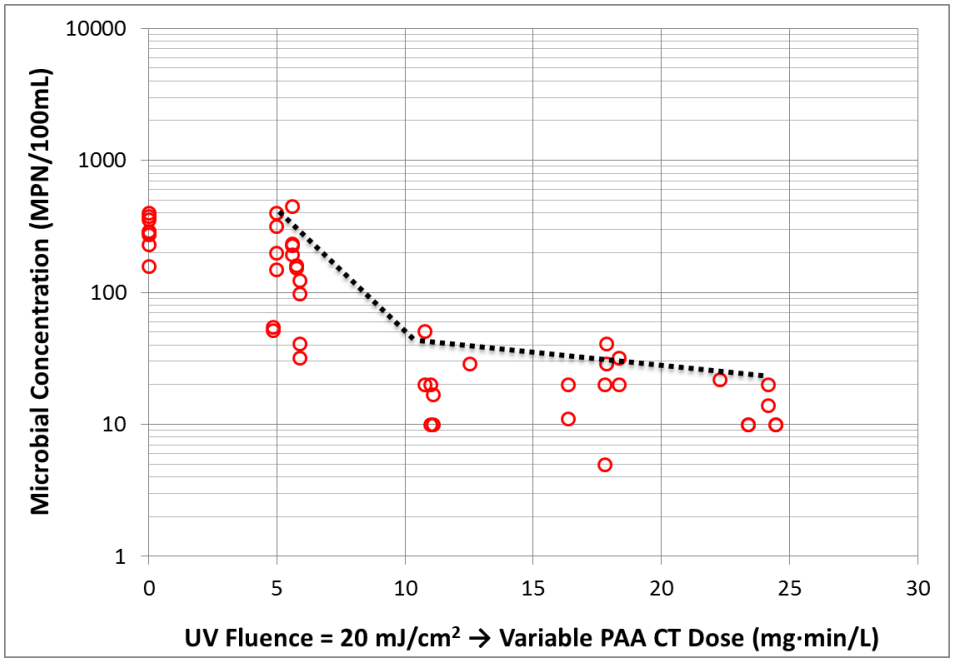

Figure 10: Inactivation of *E. coli* for UV→PAA treatment scenario where PAA treatment is preceded by a UV fluence of 20 mJ/cm^2. Dotted lines are illustrative to show general trend.

The results of this investigation show clear, consistent, and logical trends:

(i) for the initial UV treatment, increasing UV fluences treatment resulted in reduced concentration of viable *E. coli*, and

(ii) for the secondary PAA treatment, increasing PAA CTs resulted in either reduced or constant concentration of viable *E. coli*.

These "trends" are illustrated by the dotted lines in Figures 8 – 10; additionally, this sequence of treatments resulted in both the maximum and geometric mean disinfection targets being met for at least one combination of fluence and CT.

For the PAA→UV tests, PAA CTs that ranged from 10-23 mg·min/L were applied prior to UV fluence rates of 10, 15, and 20 mJ/cm^2. Figures 11 – 13 illustrates the counts of viable *E. coli* as a function of UV fluence with different levels of PAA CT applied prior to UV treatment. The data generally lacks a consistent, logical trend as in some cases there is an increase in viable counts with an increase in treatment level. These "trends" are illustrated by the schematic dotted lines in Figure 11 – 13. Further, this sequence of treatments didn't always result in the geometric mean or maximum disinfection targets being met.

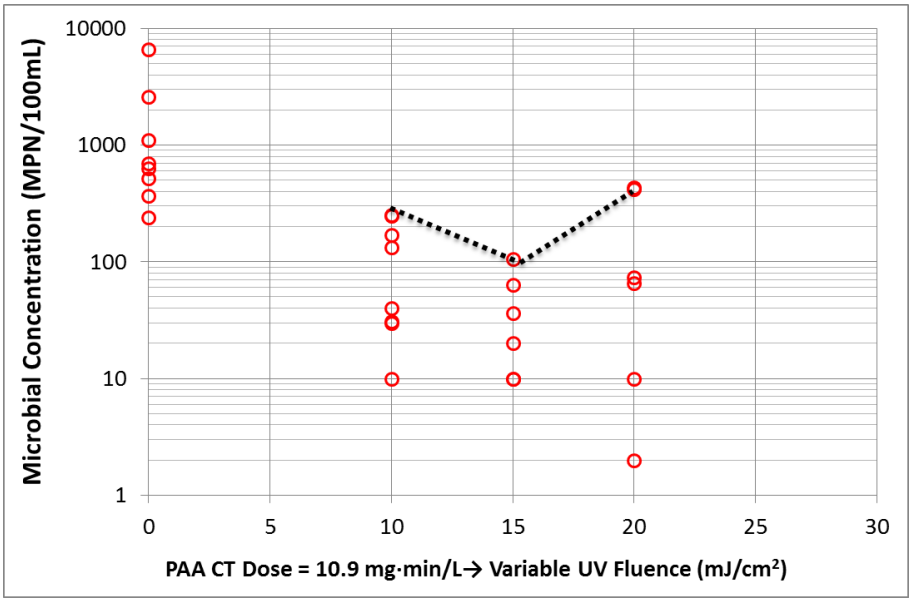

Figure 11: Inactivation of *E. coli* for PAA→UV treatment scenario where UV treatment is preceded by a PAA CT of 10.9 mg·min/L. Dotted lines are illustrative to show general trend.

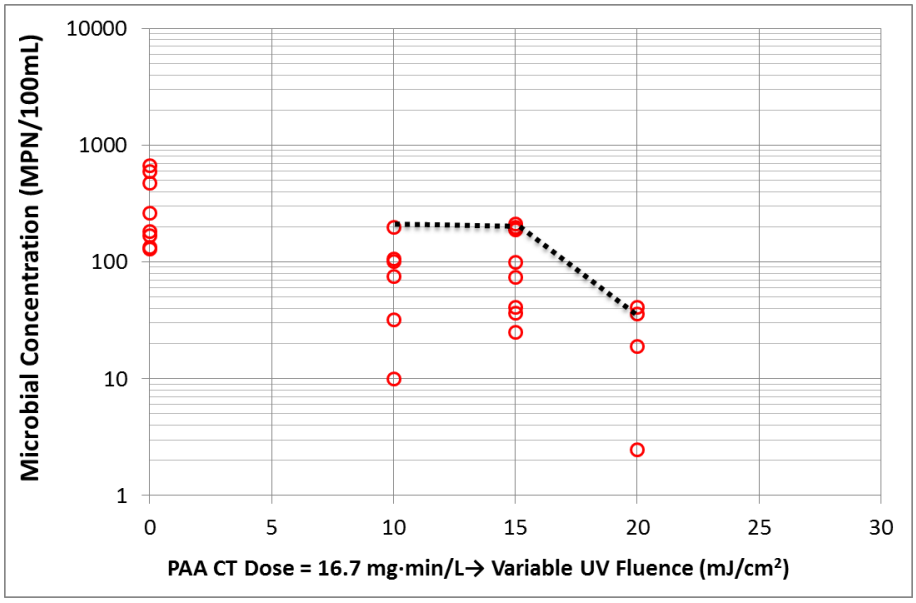

Figure 12: Inactivation of *E. coli* for PAA→UV treatment scenario where UV treatment is preceded by a PAA CT of 16.7 mg·min/L. Dotted lines are illustrative to show general trend.

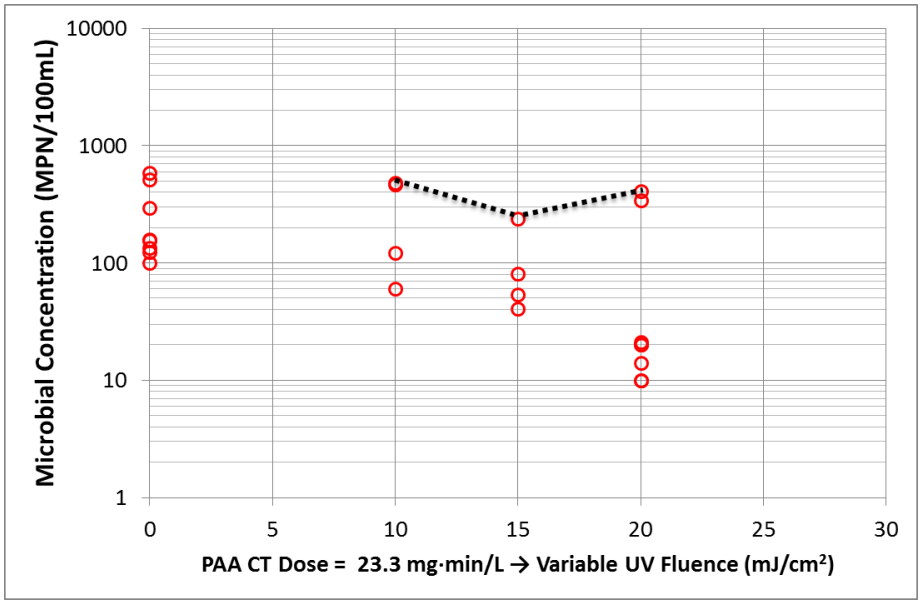

Figure 13: Inactivation of *E. coli* for PAA→UV treatment scenario where UV treatment is preceded by a PAA CT of 23.3 mg·min/L. Dotted lines are illustrative to show general trend.

For the simultaneous UV+PAA tests, UV fluence rates of 10, 15, and 20 mJ/cm^2 were used in conjunction with PAA CTs of 15-30 mg·min/L. Figure 14 – 16 illustrates the results of viable *E. coli* for the simultaneous UV and PAA tests. Data is presented by UV fluence and the respective PAA CT dose applied. In general, the data lacked clear trends; increasing levels of treatments (i.e., higher PAA CTs and UV fluences) did not result in continuously increasing levels of disinfection. Moreover, for reasons not yet evident, the simultaneous treatment scheme could not achieve the geomean or maximum disinfection targets.

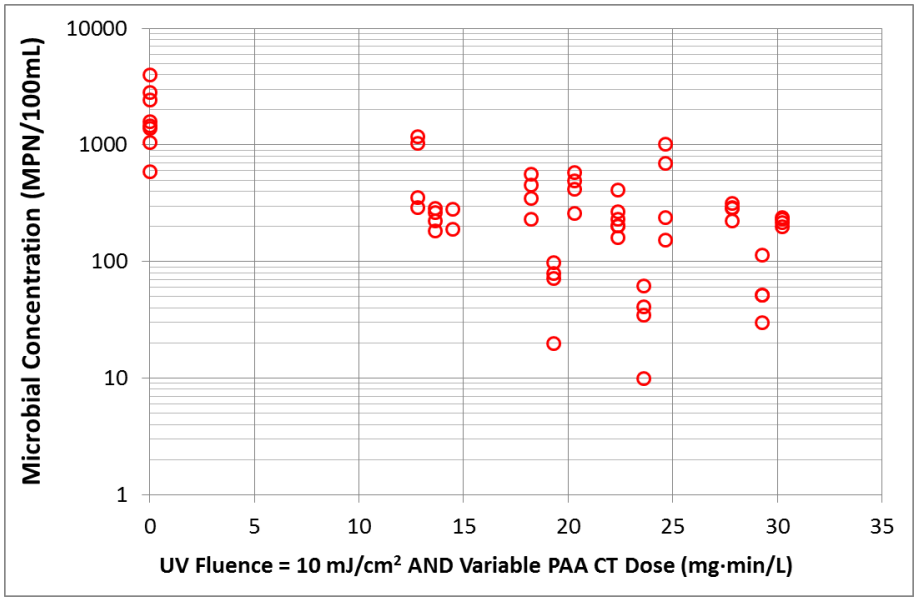

Figure 14: Inactivation of *E. coli* for UV+PAA treatment scenario where data is plotted for fixed UV fluences of 10 mJ/cm^2 and variable PAA CT doses.

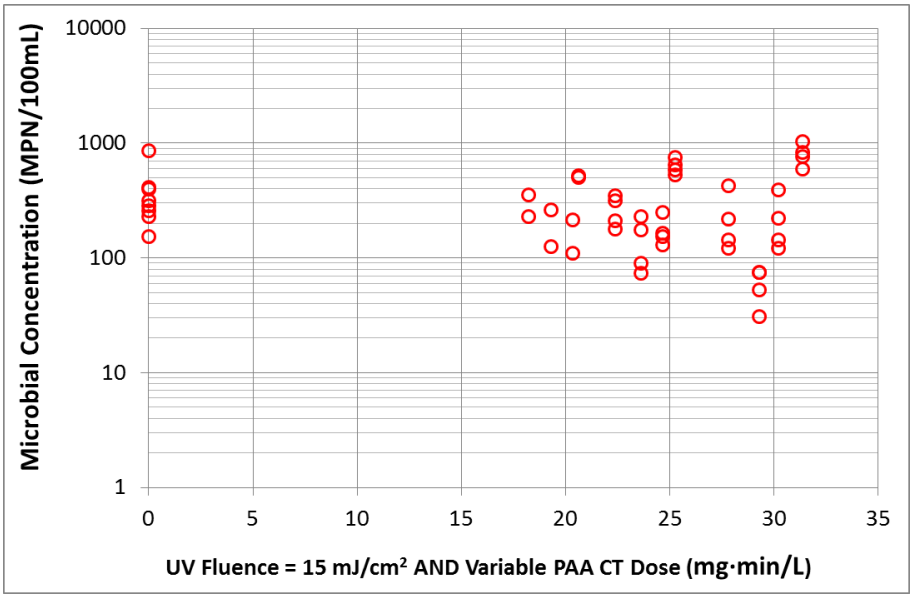

Figure 15: Inactivation of *E. coli* for UV+PAA treatment scenario where data is plotted for fixed UV fluences of 15 mJ/cm^2 and variable PAA CT doses.

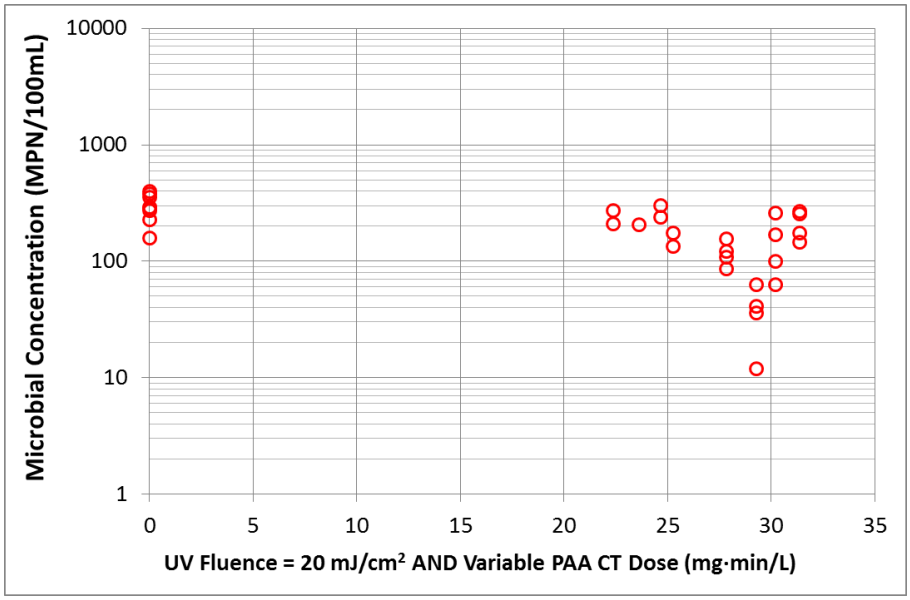

Figure 16: Inactivation of *E. coli* for UV+PAA treatment scenario where data is plotted for fixed UV fluences of 20 mJ/cm^2 and variable PAA CT doses.

5.5 Modeling the sequential UV→PAA

Because the treatment sequence of UV followed by PAA resulted in the most consistent attainment of disinfection targets, this scheme was selected for further analyses including mechanistic modelling and sizing. For the mechanistic modelling, an approach similar to Equation 3 was applied. Equation 3 presents a mechanistic approach where populations of microbes are separated based on their susceptibility to a single disinfectant (UV or PAA) and each population having its own inactivation rate kinetics. For the cases where two disinfectants are applied (UV and PAA) we propose separating the microbes into four populations: (A_0) easy to inactivate by UV and PAA, (B_0) easy to inactivate by UV, hard to inactivate by PAA, (C_0) hard to inactivate by UV, easy to inactivate by PAA, and (D_0) hard to inactivate by UV, hard to inactivate by PAA. Figure 17 provides a conceptual illustration of this mechanistic approach.

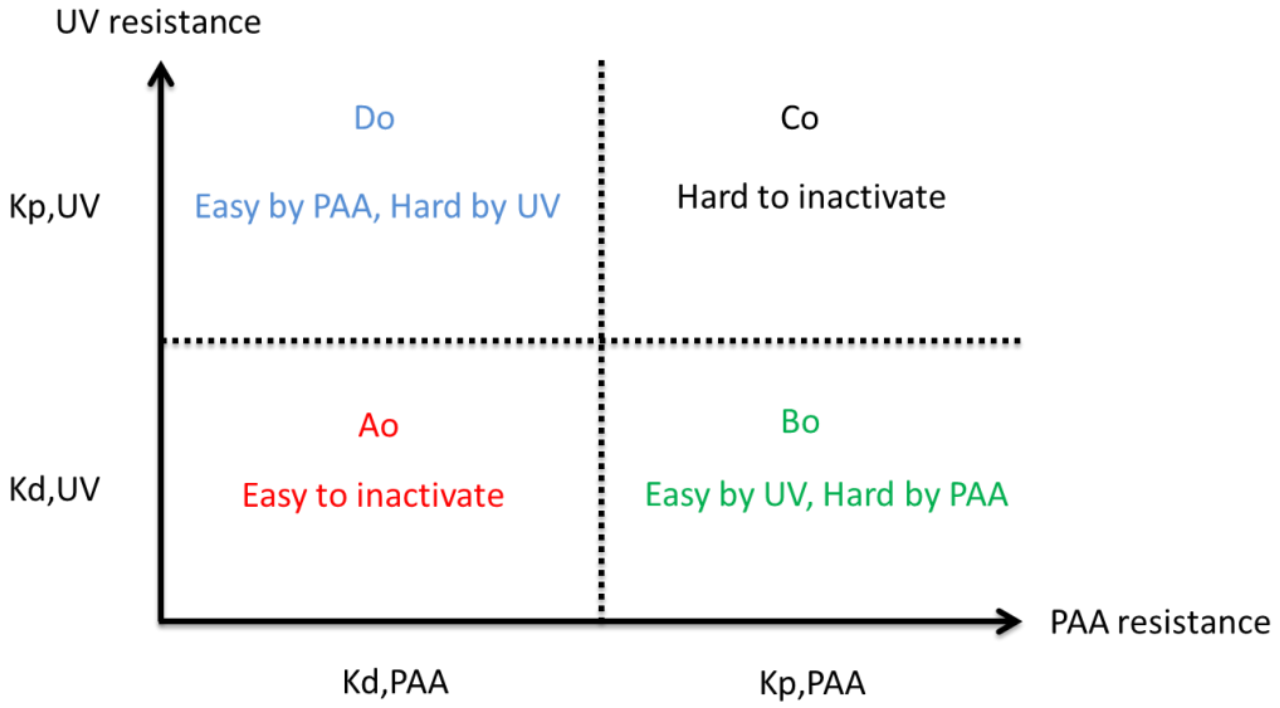

Figure 17: Four population mechanistic approach to model binary disinfection system consisting of UV and PAA disinfectants.

Inactivation mechanisms for this system are represented in Figure 18 and Equation 4 is used to quantify the concentration of viable organisms after disinfection.

$$N_{total,viable\ (UV_{dose},PAA_{dose})} = A2_{viable} + B2_{viable} + C2_{viable} + D2_{viable}$$ [Equation 4]

where,

$N_{total,viable\ (UVdose,PAAdose)}$ is the total concentration of viable *E. coli* remaining after UV and PAA treatment; MPN / 100 mL

$A2_{viable}$ is the concentration of viable organisms from population A_0 remaining after UV and PAA treatment

$B2_{viable}$ is the concentration of viable organisms from population B_0 remaining after UV and PAA treatment mL

$C2_{viable}$ is the concentration of viable organisms from population C_0 remaining after UV and PAA treatment mL

$D2_{viable}$ is the concentration of viable organisms from population D_0 remaining after UV and PAA treatment mL

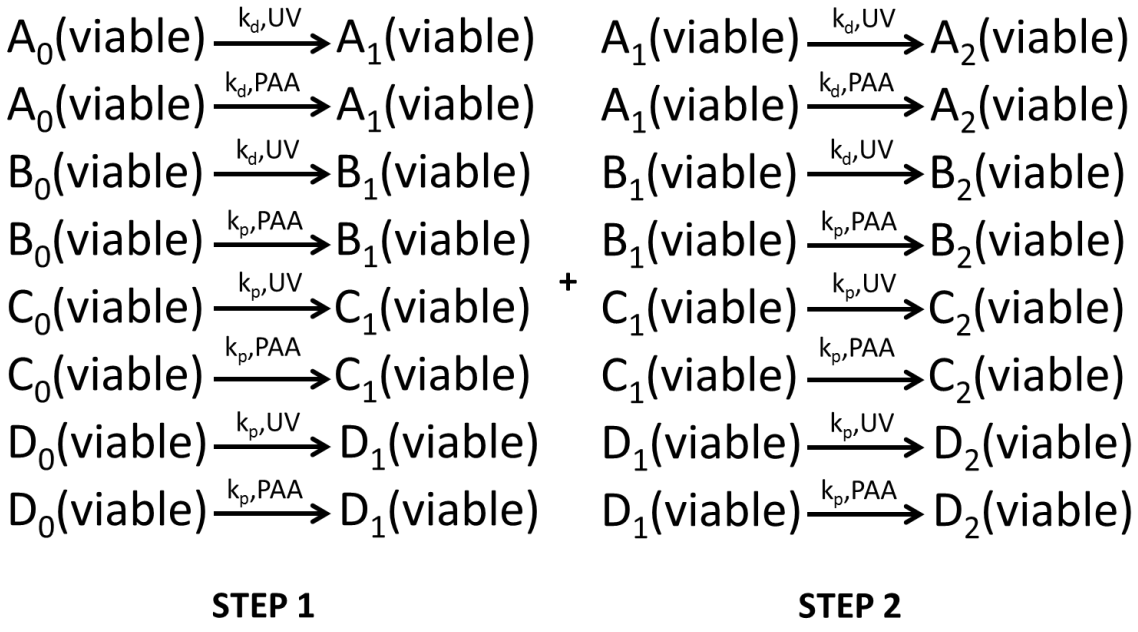

Figure 18: Inactivation mechanisms presenting the inactivation routes and respective first order inactivation rate constants for the proposed four population system with binary disinfectants.

The four population, binary disinfectant model was fitted to the UV only, PAA only, and UV→PAA experimental data to estimate model parameters: A_0, B_0, C_0, D_0, $K_{d,UV}$, $K_{d,PAA}$, $K_{p,UV}$, and $K_{p,PAA}$. The

resulting model is shown with observed results for UV only and PAA only (Figure 19) and for UV→PAA (Figure 20). Figure 21 provides a comparison between actual results and model predicted concentrations of viable *E. coli*. The four population, binary disinfectant model was able to reasonably predict the effect of UV only, PAA only, and UV→PAA disinfection of *E. coli*.

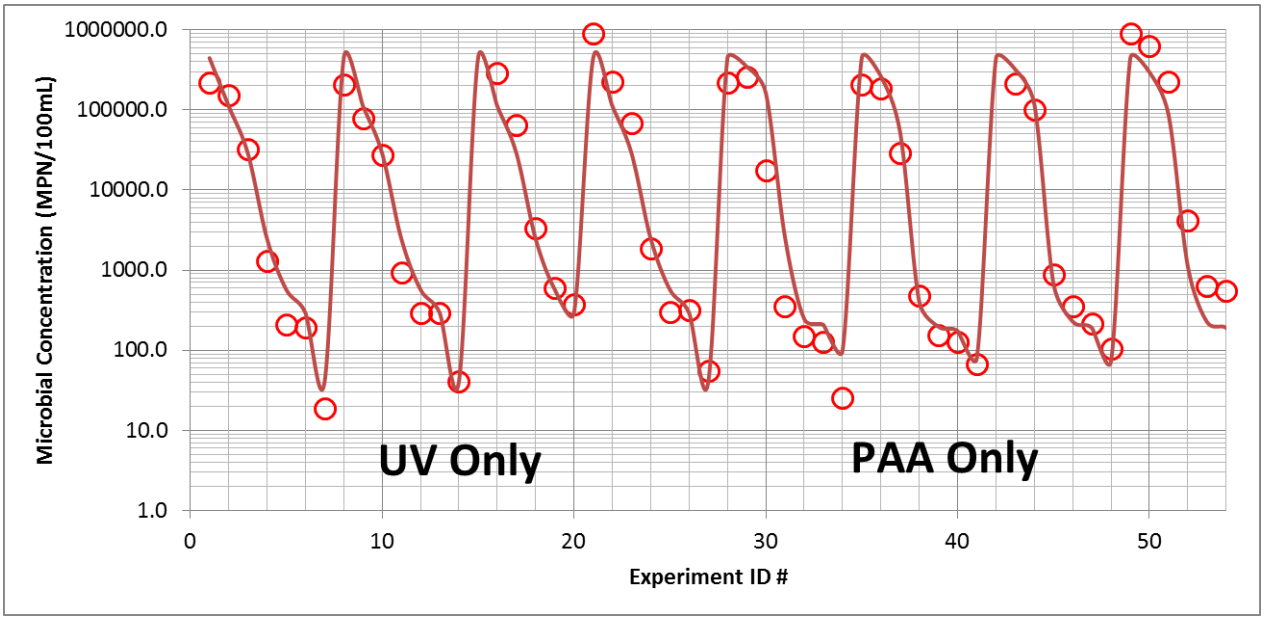

Figure 19: Experimental results from inactivation using UV or PAA alone (circles) and predicted values using the four population, binary disinfectant model.

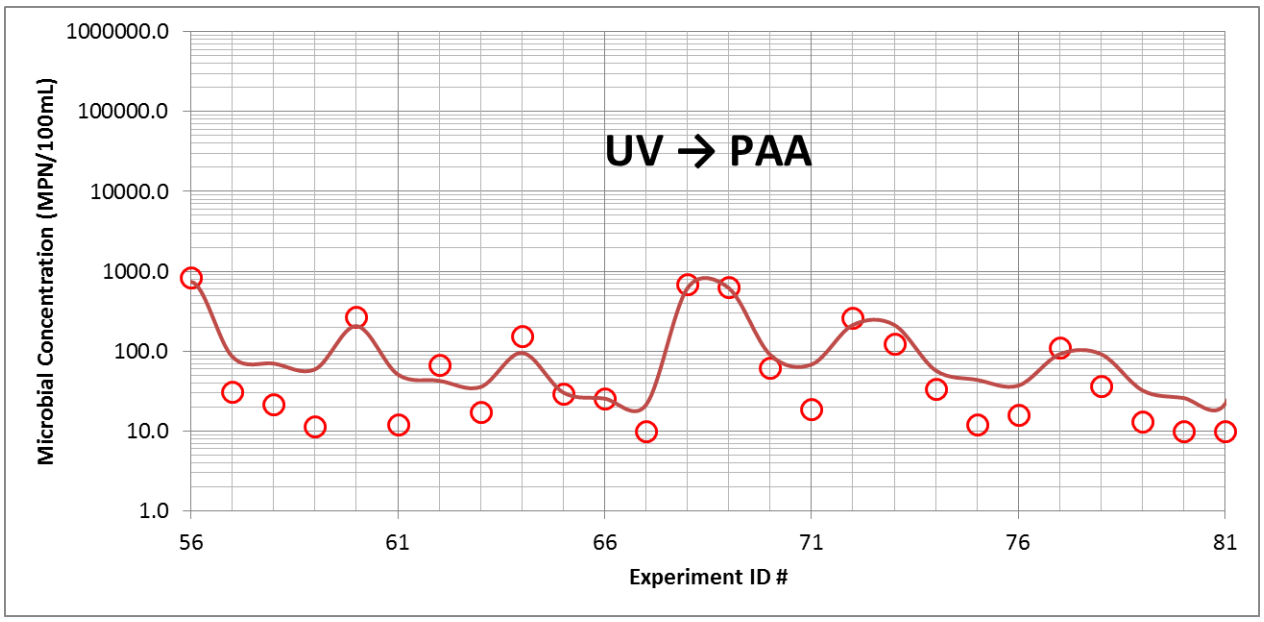

Figure 20: Experimental results from inactivation using UV→PAA (circles) and predicted values using the four population, binary disinfectant model.

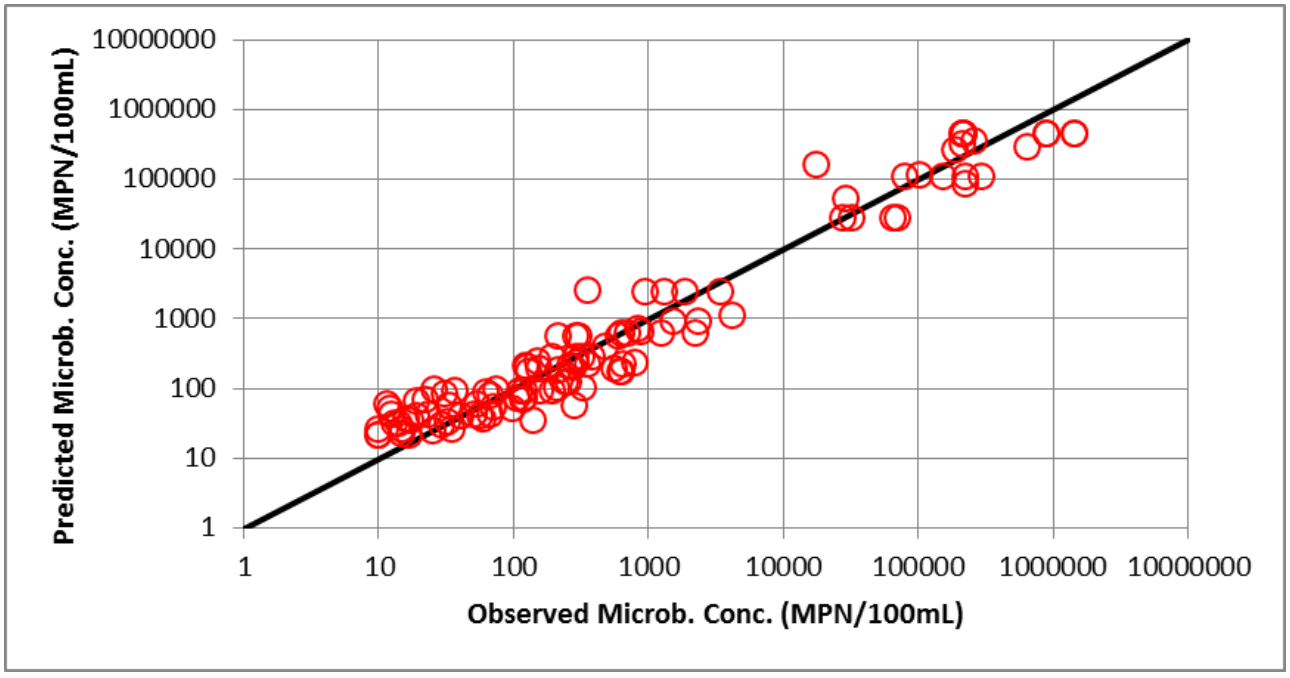

Figure 21: Observed versus model predicted combinations for the UV only, PAA only tests and sequential UV PAA tests. Diagonal line illustrates a perfect fit line.

5.6 Summary of Results

The key results that were determined during this study are summarized here:

- There was no observed difference in the inactivation kinetics of 22% and 15% PAA solutions.
- There was no observed difference in the decomposition kinetics of 22% and 15% PAA solutions.
- A PAA CT dose of 49.2 mg·min/L was required to meet the plant's *E. coli* disinfection target of 63 MPN / 100 mL.
- A UV fluence of 20.1mJ/cm^2 min was required to meet the plant's *E. coli* disinfection target of 63 cfu / 100 mL.
- Of the UV and PAA combined treatment schemes, the UV followed by PAA scheme performed the best in that it consistently met disinfection targets.
- A mechanistic model was developed to predict *E. coli* inactivation by the UV only, PAA only, and UV followed by PAA treatment schemes.
- The mechanistic model was used to determine the combination of UV fluence and PAA CT doses required to meet the plant's *E. coli* disinfection target of 63 MPN / 100 mL.
- The developed correlation can be used to size a combined UV and PAA system as well as perform economic analyses to maximized savings in capital, operating, or net present costs.

6 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the four population, binary model that was developed with estimated parameters, could be used to size the combination of UV fluences and PAA CT doses that would be required to achieve a 30-day geomean disinfection target of 63 MPN/100 mL at full scale. Figure 22 provides a graphical illustration of the combination of disinfectant doses predicted to be required where UV precedes PAA. This plot shows that as the delivered UV fluence is decreased, PAA can be brought online to supplement UV and meet the disinfection target.

It is recommended that this correlation be used to provide disinfection system sizing for a UV + PAA combination system. Although it is currently outside of the scope of work of this effort, it is recommended that the conceptual evaluation of disinfection economics, including operating and capital costs, for the various UV and PAA combinations be developed to support the disinfection system selection process.

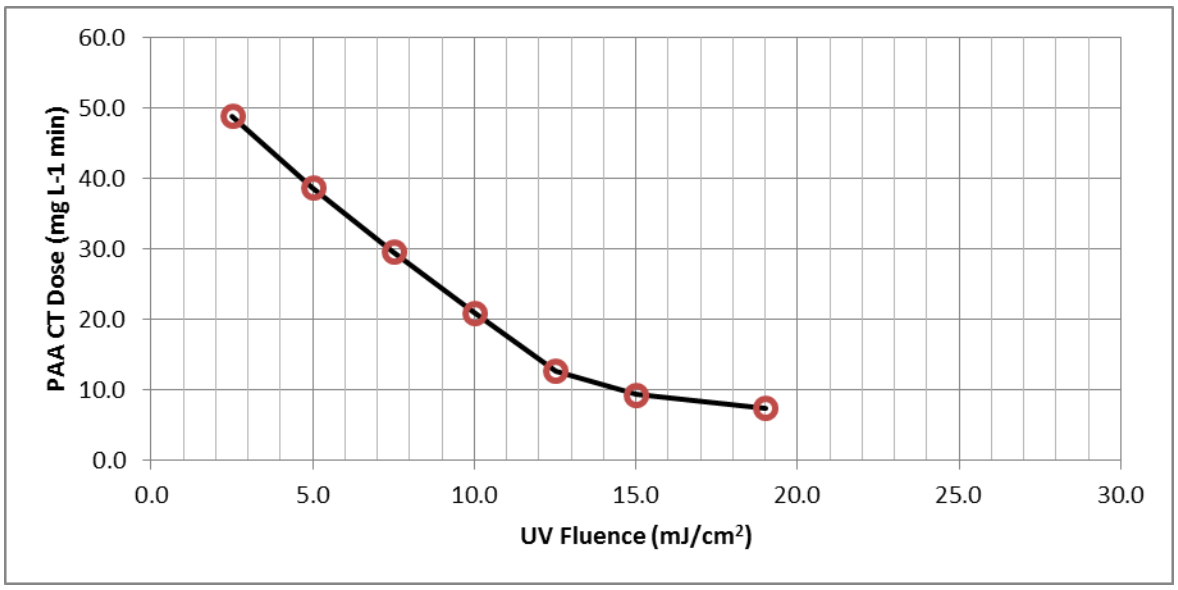

Figure 22: Model predicted combinations of PAA dose and UV fluence required to achieve an *E. coli* disinfection target of 63 cfu / 100 mL when applying the sequential **UV→PAA** treatment process.

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APPENDIX A – TEST PROTOCOL

City of Memphis, TN – Maxson WRRF Site Test Protocol - UV and PAA Disinfection

1) SUMMARY

Two (2) secondary effluent samples will be collected daily from the Maxson WRRF and treated by UV and PAA disinfection. Testing will be conducted over a period of three (3) days during the week of Sept 21st. The experiment test matrix described below will be conducted on each of the 6 water samples.

2) OBJECTIVE

Evaluate various process design scenarios and operating parameters for a combined UV and PAA disinfection system by running batch disinfection studies under different UV and PAA treatment conditions.

3) EXPERIMENT TEST MATRIX

These experiments will include variable PAA and UV dosages, alone and in combination. The detailed experimental plan is outlined as:

a. PAA demand decay test (PAA residuals will be measured at each contact time).
b. E. coli disinfection over a PAA dosage range: 0, 5, 10, 15, 20, and 40 mg/L min.
c. E. coli disinfection over a UV dosage range: 0, 2.5, 5, 10, 20 and 40 mJ/cm^2.
d. E. coli disinfection at UV→PAA dosages: Sample pre-treated by UV at 10, 15 and 20 mJ/cm^2 dosages followed by PAA dosages of 0, 5, 10, 15, 20 mg/L min.
e. E. coli disinfection at PAA→UV dosages: Sample pre-treated by PAA at CT dose of 5, 10, 15 and 20 mg/L min, followed by irradiation using UV fluences of 0, 10, 15, and 20 mJ/cm^2.
f. E. coli disinfection at UV+PAA dosages: Simultaneous addition of PAA and UV at CT doses in the range of 5-10, 10-15, and 15-20 mg/L min and UV doses of 10, 15, and 20 mJ/cm^2.

The complete test matrix is shown in Table 1. Two (2) secondary effluent samples will be collected each day for three (3) days. Samples will be collected in attempt to capture average flow and peak flow

conditions. For example, the first sample would be collected at 7:00 AM and the second around 1:00 PM. Ten (10) liters of secondary effluent will be collected at each time. Two (2) liters of this sample will be sent to Trojan as a backup. Select experiments will be completed in duplicate.

All the samples will be tested using the same test matrix illustrated in Table 1. UV tests will be conducted using the 50 mL volumes in 60 mL petri dishes. PAA tests will be conducted using appropriate size beakers (500 – 2000 mL)

Table 1 – Test matrix for UV/PAA experiments

Test ID #	Treatment process	UV fluence (mJ/cm^2)	PAA CT (mg/L min)	Test Parameters
1	Control	0	0	E.coli
2	PAA alone	0	2.5	PAA residual, E.coli
3	PAA alone	0	5	PAA residual, E.coli
4	PAA alone	0	10	PAA residual, E.coli
5	PAA alone	0	15	PAA residual, E.coli
6	PAA Alone	0	20	PAA Residual, E. coli
7	PAA Alone	0	40	PAA Residual, E. coli
8	UV alone	2.5	0	E.coli
9	UV alone	5	0	E.coli
10	UV alone	10	0	E.coli
11	UV alone	15	0	E.coli
12	UV Alone	20	0	E. coli
13	UV Alone	40	0	E. coli
14	UV+PAA	10	5	PAA residual, E.coli

15	UV+PAA	10	10	PAA residual, E.coli
16	UV+PAA	10	15	PAA residual E.coli
17	UV+PAA	10	20	PAA residual, E.coli
18	UV+PAA	15	5	PAA residual, E.coli
19	UV+PAA	15	10	PAA residual, E.coli
20	UV+PAA	15	15	PAA residual E.coli
21	UV+PAA	15	20	PAA residual, E.coli
22	UV+PAA	20	5	PAA residual, E.coli
23	UV+PAA	20	10	PAA residual, E.coli
24	UV+PAA	20	15	PAA residual, E.coli
25	UV+PAA	20	20	PAA residual, E.coli
26	PAA+UV	10	5	PAA residual, E.coli
27	PAA+UV	15	5	PAA residual, E.coli
28	PAA+UV	20	5	PAA residual, E.coli
29	PAA+UV	10	10	PAA residual, E.coli
30	PAA+UV	15	10	PAA residual, E.coli
31	PAA+UV	20	10	PAA residual, E.coli
32	PAA+UV	10	15	PAA residual, E.coli
33	PAA+UV	15	15	PAA residual, E.coli
34	PAA+UV	20	15	PAA residual, E.coli
35	PAA+UV	10	20	PAA residual, E.coli

36	PAA+UV	15	20	PAA residual, E.coli
37	PAA+UV	20	20	PAA residual, E.coli
38	Simult. PAA+UV	10	5 – 10	PAA residual, E.coli
39	Simult. PAA+UV	10	5 – 10	PAA residual, E.coli
40	Simult. PAA+UV	10	10 – 15	PAA residual, E.coli
41	Simult. PAA+UV	10	15 – 20	PAA residual, E.coli
42	Simult. PAA+UV	15	10 – 15	PAA residual, E.coli
43	Simult. PAA+UV	15	10 – 15	PAA residual, E.coli
44	Simult. PAA+UV	15	15 – 20	PAA residual, E.coli
45	Simult. PAA+UV	20	15 – 20	PAA residual, E.coli
46	Simult. PAA+UV	20	15 – 20	PAA residual, E.coli
47	Simult. PAA+UV	10	5 – 10	PAA residual, E.coli
48	Simult. PAA+UV	10	10 – 15	PAA residual, E.coli
49	Simult. PAA+UV	10	15 – 20	PAA residual, E.coli
50	Simult. PAA+UV	15	10 – 15	PAA residual, E.coli
51	Simult. PAA+UV	15	15 – 20	PAA residual, E.coli
52	Simult. PAA+UV	20	15 – 20	PAA residual, E.coli

The total number of tests per sample is shown in Table 2.

Table 2 – Total numbers of samples and volume

Test	Microbe	PAA	Volume (mL)
Demand &Decay	0	5	500
Controls / Calibration	12	6	600
PAA alone / PAA+UV	50	6	1500
UV alone / UV+PAA	46	12	1200
Simult. PAA+UV	36	15	750
Total number of samples or volume	144	44	4550

4) SCHEDULE AND TEAM MEMBERS

a) This experiment will be conducted during the week of Sept 21, 2015.
   a. Sunday: Arrival in Memphis
   b. Monday: Plant survey and prep work
   c. Tuesday, Wednesday, Thursday: Sample collection and testing days.
      i. 1st sample collected ca. 07:00. Complete test matrix (ca. 5 – 6 hours)
      ii. 2nd sample collected ca. 13:00. Complete test matrix (ca. 5 – 6 hours)
   d. Friday: Buffer day for extra tests if needed

b) On-site Team:
   a. PAA work: Adrian Murray, PhD, Trojan Application Specialist
   b. UV work: Wenjun Sun, PhD, Trojan Application Specialist
   c. Josh Goldman, PhD, CDM Smith, Environmental Engineer

5) METHODS

Analytical Methods

UV collimated beam and PAA measurements will be conducted following the established SOPs developed by Trojan Technologies.

E. coli measurements will be performed by Waypoint Analytical (Memphis, TN) following the Idexx Colisure protocol.

Color and UVT will be measured on-site by CDM. TSS, COD, and BOD will be measured by an external lab, arranged by CDM.

UV irradiation times and PAA contact times provided in the test plan below are estimates based on previous experiments performed by Trojan Technologies on Maxson water samples. The actual UV irradiation and PAA contact times to be used will be determined for each collected sample prior to analysis.

Test procedures

1. Prepare PAA stock solution (1000 mg/L) from 22% PAA, measure the concentration using titration method (see SOP - PAA production and testing) and with CHEMetrics test kit.
2. Prepare a second PAA stock solution (10,000 mg/L) from 22% PAA, and measure the concentration using titration method (see SOP - PAA production and testing) and with CHEMetrics test kit..
3. Prepare sodium bisulfite stock solution (0.01M) from commercial standard.
4. Collect 6 x 100 mL of sample and set aside as controls for E. coli analysis.
   4.1. Suggested dilutions are: 4 log, 3 log.
5. **Conduct PAA demand/decay pre-test.**
   - 5.1 Measure 250 mL of sample and pour into 500 mL beaker.
   - 5.2 Add appropriate volume of PAA stock solution (1000 mg/L) to obtain 4 mg/L PAA in the 250 mL sample. Start timer immediately after addition. The stir rate for PAA reaction is level 10.
   - 5.3 Measure residual PAA (by removing 25 mL and adding to CHEMetrics test kit) at time intervals of:
     - 5.3.1 0.5 min
     - 5.3.2 2 min
     - 5.3.3 4 min
     - 5.3.4 8 min
     - 5.3.5 16 min
   - 5.4 Quench sample with 0.01 M $NaHSO_3$ stock solution (stoichiometric) and discard.
   - 5.5 Measure background PAA reading for the water sample, in triplicate.
   - 5.6 Record actual concentration of PAA added to sample by dosing in the same volume of PAA stock solution into 250 mL DI water, in triplicate.
   - 5.7 Record measured PAA residuals in the file “Decay Demand Analysis for CT Estimates”.
   - 5.8 Repeat steps 5.1-5.7 one more time on the same water sample.
   - 5.9 Repeat steps 5.1 – 5.7 with PAA stock solution (10,000 mg/L)

6. Conduct PAA / PAA +UV test:

6.1 Measure 1500 mL of sample and pour into 2000 mL beaker.

6.2 Target a PAA residual of approximately 2 mg/L after 30 seconds, based on step 3, calculate the time required to achieve the above CT (to be estimated with a preliminary decay test), keeping in mind that the actual CT would need to be recalculated for the actual residual PAA concentration measured during PAA disinfection experiments.

6.3 Add PAA concentration calculated from step 5.2, start timer immediately after addition.

6.4 Measure residual PAA (by removing 25 mL and adding to CHEMetrics test kit) at required CT (approx.. 1:01, 2:05, 4:19, 6:44, 9:21 and 23:01 min:sec)

6.5 At the following times, the designated volume of sample is withdrawn and a stoichiometric amount of sodium bisulfite stock solution is added to quench the residual (to ensure immediate quenching at the required time).

6.5.1 For time 1:01, collect 100 mL of sample for microbial testing

6.5.2 For times 2:05 – 9:21, collect 300 mL of sample for microbial testing and to be used for PAA+UV testing

6.5.3 For time 23:01, collect 100 mL of sample for microbial testing

6.6 For each 300 mL subsample collected for PAA+UV analysis (times 2:05 – 9:21), subsample 50 mL for microbial testing. Use the remaining 250 mL to prepare 50 mL samples for UV irradiation.

6.6.1 Measure the UV intensity of the collimated beam to use in calculating the irradiation time (based on the spreadsheet developed by Trojan Technologies – see SOP-collimated beam). The stir rate for UV collimated beam should be set at level 10.

6.6.2 Irradiate 50 mL volume from the subsample to a fluence of 10 mJ/cm^2. Retain the 50 mL of sample for E. coli analysis.

6.6.3 To a new 50 mL sample, irradiate to a fluence of 15 mJ/cm^2. Retain the 50 mL of sample for E. coli analysis.

6.6.4 To a new 50 mL sample, irradiate to a fluence of 20 mJ/cm^2. Retain the 50 mL of sample for E. coli analysis.

6.6.5 Repeat 6.6.1 – 6.6.4 for each 300 mL subsample.

Table 3 - Sample dilutions for E.coli enumeration

Test ID #	UV Fluence (mJ/cm^2)	PAA CT (mg/L min)	Dilution
2	0	2.5	4 log, 3 log
3	0	5	3 log, 2 log
26	10	5	2 log, 1 log
27	15	5	1 log, none
28	20	5	none
4	0	10	2 log, 1 log
29	10	10	1 log, none
30	15	10	none
31	20	10	none
5	0	15	1 log, none
32	10	15	none
33	15	15	none
34	20	15	none
6	0	20	none
35	10	20	none
36	15	20	none
37	20	20	none
7	0	40	none

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7. Conduct UV+PAA test:

7.1 Measure the UV intensity of the collimated beam to use in calculating the irradiation time (based on the spreadsheet developed by Trojan Technologies – see SOP-collimated beam).The stir rate for UV collimated beam should be set at level 10.
7.2 Irradiate 50 mL volume at the specified fluence, ex. 10 mJ/cm^2,
7.3 Repeat step 7.2 six more times to obtain 350 mL of irradiated sample.
7.4 Withdraw 50 mL of sample for E. coli analysis.
7.5 Spike the leftover UV irradiated composite batch with PAA to obtain a 2 mg/L residual (after 30 seconds), and start timer.
7.6 Withdraw samples: 25mL for PAA analysis and 50 mL for E. coli (to be quenched with $NaHSO_3$) at 2:05, 4:19, 6:44 and 9:21 min:sec.
7.7 Repeat steps 7.5 – 7.6 for remaining UV intensities (15 and 20 mJ/cm^2)

Table 4 – Suggested dilutions for E.coli coliform enumeration

Test ID #	UV Fluence (mJ/cm^2)	PAA CT (mg/L min)	Dilutions
10	10	0	2 log, 1 log
14	10	5	1 log, none
15	10	10	none
16	10	15	none
17	10	20	none
11	15	0	1 log, none
18	15	5	none
19	15	10	none
20	15	15	none
21	15	20	none
12	20	0	none
22	20	5	none

23	20	10	none
24	20	15	none
25	20	20	none

8. Conduct UV alone test:

8.1 Repeat step 7.1 to determine the irradiation time required for each target UV dosage (2.5, 5, 40 mJ/cm^2).

8.2 Use 50 mL secondary effluent samples and irradiate using the calculated durations from step 6.1

8.3 Retain the entire 50 mL of sample for E. coli analysis.

8.3 Repeat steps 8.1 – 8.3 for remaining UV fluences.

Table 5 – Suggested sample dilutions for E. coli enumeration

Test ID #	UV Fluence (mJ/cm^2)	Dilutions
8	2.5	4 log, 3 log
9	5	3 log, 2 log
13	40	none

9. Conduct simultaneous UV+PAA:

9.1. A detailed test matrix for this section is provided as an appendix.

9.2. Place 50 mL sample under UV lamp while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously)

9.3. Irradiate sample for 3:32 (ca. 10 mJ/cm^2). Remove sample from UV, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use 10 mL sub-sample to measure PAA residual concentration. Use the remaining 40 mL of sample for E. coli analysis.

9.4. For a new sample, irradiate for 3:32 (ca. 10 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 0:47, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.5. For a new sample, irradiate for 3:32 (ca. 10 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 3:12, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.6. For a new sample, irradiate for 3:32 (ca. 10 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 5:49, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.7. For a new sample, irradiate for 5:18 (ca. 15 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample from UV, and remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.8. For a new sample, irradiate for 5:18 (ca. 15 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 1:26, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.9. For a new sample, irradiate for 5:18 (ca. 15 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 4:03, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.10. For a new sample, irradiate for 7:05 (ca. 20 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample from UV, and remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

9.11. For a new sample, irradiate for 7:05 (ca. 20 mJ/cm^2), while simultaneously adding PAA (spike to 2 mg/L after residual, as calculated previously). Remove sample and let stir additional 2:17, remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10. Conduct simultaneous PAA+UV:

10.1. A detailed test matrix for this section is provided as an appendix.

10.2. Place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 0:47 and then place under UV lamp. Stir for additional 3:32 (ca. 10 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10.3. For a new sample, place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 3:12 and then place under UV lamp. Stir for additional 3:32 (ca. 10 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10.4. For a new sample, place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 5:49 and then place under UV lamp. Stir for additional 3:32 (ca. 10 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10.5. For a new sample, place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 1:26 and then place under UV lamp. Stir for additional 5:18 (ca. 15 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10.6. For a new sample, place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 4:03 and then place under UV lamp. Stir for additional 5:18 (ca. 15 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

10.7. For a new sample, place 50 mL sample on stir plate and add PAA (spike to 2 mg/L after residual, as calculated previously) Stir sample for 2:17 and then place under UV lamp. Stir for additional 7:04 (ca. 20 mJ/cm^2) and then remove from lamp. Remove 10 mL for PAA analysis, and quench remaining sample with $NaHSO_3$. Use the remaining 40 mL of sample for E. coli analysis.

Table 6 – Suggested sample dilutions for E. coli enumeration

Test ID #	UV Fluence (mJ/cm^2) before PAA	PAA CT (mg/L min)	UV Fluence (mJ/cm^2) after PAA	Dilutions
38	10	5 – 10	-	1 log, none
39	10	5 – 10	-	1 log, none
40	10	10 – 15	-	none

41	10	15 – 20	-	none
42	15	10 – 15	-	none
43	15	10 – 15	-	none
44	15	15 – 20	-	none
45	20	15 – 20	-	none
46	20	15 – 20	-	none
47	-	5 – 10	10	1 log, none
48	-	10 – 15	10	none
49	-	15 – 20	10	none
50	-	10 – 15	15	none
51	-	15 – 20	15	none
52	-	15 – 20	20	none

Material

- Collimated beam, Extra lamp for collimated beam, radiometer
- CHEMetrics PAA analyzer
- PAA test kits
- Sample vials for microbial analysis
- UVT detector
- PAA stock solution, provided on site
- Sodium sulfite for quenching
- wash bottle
- Sample bottles for collecting samples
- Cooler for transporting samples
- micropipettes, 0.1 – 1 mL, 10 – 100 µL.
- pipette tips

- autopipetter, plus larger pipettes (10 – 50 mL)
- grad cylinders, 1 x 50 mL, 1 x 500 mL
- 60 mL petri dishes with stir bars
- 500 mL beakers, 2000 mL beakers
- stop watch / timer
- stir plates
- Kim wipes
- labels, markers, tape, pens, etc
- small, brown glass sample bottles to prepare stock solutions of PAA and quench NaHSO3
- Cerium Sulfate
- sodium thiosulfate
- hach sulfate 1 test packetes
- ferroin indicator
- burret for PAA titration
- 50 mL Erlenmeyer flasks

Appendix : *Test matrix for simultaneous UV+PAA and PAA+UV*

Test ID #	Treatment process	UV irradiation time (min)	UV Dosage (mJ/cm^2)	Additional PAA contact time (min)	Total Contact time (min)	Total PAA CT (mg/L min)
38	Simult. UV+PAA	3:32	10	0	3:32	between 5-10
39	Simult. UV+PAA	3:32	10	0:47	4:19	between 5-10
40	Simult. UV+PAA	3:32	10	3:12	6:44	between 10-15
41	Simult. UV+PAA	3:32	10	5:49	9:21	between 15-20
42	Simult. UV+PAA	5:18	15	0	5:18	between 10-15
43	Simult.	5:18	15	1:26	6:44	between

	UV+PAA					10-15
44	Simult. UV+PAA	5:18	15	4:03	9:21	between 15-20
45	Simult. UV+PAA	7:04	20	0	7:04	between 15-20
46	Simult. UV+PAA	7:04	20	2:17	9:21	between 15-20

Sample #	**Treatment process**	**Initial PAA contact time (min)**	**UV irradiation time (min)**	**UV Dosage (mJ/cm^2)**	**Total Contact time (min)**	**Total PAA CT (mg/L min)**
47	Simult. PAA+UV	0:47	3:32	10	4:19	between 5-10
48	Simult. PAA+UV	3:12	3:32	10	6:44	between 10-15
49	Simult. PAA+UV	5:49	3:32	10	9:21	between 15-20
50	Simult. PAA+UV	1:26	5:18	15	6:44	between 10-15
51	Simult. PAA+UV	4:03	5:18	15	9:21	between 15-20
52	Simult. PAA+UV	2:17	7:04	20	9:21	between 15-20

APPENDIX B – RAW DATA

These tests were performed on Sep 21. The goal was to compare 22% and 15% PAA formulations for inactivation of *E. coli.* Each stock was prepared to 0.1%

Sample ID	PAA product	Contact Time (min)	E-coli (MPN/100 mL)
DDTest-0		0	411000
DDTest-0 Dilution #2		0	700000
DDTest-22-1	22%	1	488000
DDTest-22-1 Dilution #2	22%	1	450000
DDTest-22-4	22%	4	242000
DDTest-22-4 Dilution #2	22%	4	326000
DDTest-22-8	22%	8	2850
DDTest-22-8 Dilution #2	22%	8	2800
DDTest-22-16	22%	16	236
DDTest-22-16 Dilution #2	22%	16	270
DDTest-22-32	22%	32	111
DDTest-22-32 Dilution #2	22%	32	190
DDTest-15-1	15%	1	461000
DDTest-15-1 Dilution #2	15%	1	370000
DDTest-15-4	15%	4	>242000
DDTest-15-4 Dilution #2	15%	4	308000
DDTest-15-8	15%	8	7700
DDTest-15-8 Dilution #2	15%	8	7500
DDTest-15-16	15%	16	770

DDTest-15-16 Dilution #2	15%	16	1120
DDTest-15-32	15%	32	51
DDTest-15-32 Dilution #2	15%	32	100

These tests were performed on Sep 21. The goal was to compare the decomposition of 22% and 15% PAA. Also the effect of dilution to 0.1% and 1% was investigated.

PAA product	**Contact Time (min)**	**PAA concentration (mg/L)**
22% diluted to 0.1%	0	4.77
22% diluted to 0.1%	0.2	1.37
22% diluted to 0.1%	0.4	1.36
22% diluted to 0.1%	0.8	1.34
22% diluted to 0.1%	1	1.33
22% diluted to 0.1%	2	1.29
22% diluted to 0.1%	4	1.20
22% diluted to 0.1%	8	1.03
22% diluted to 0.1%	16	0.77
22% diluted to 0.1%	32	0.43
15% diluted to 0.1%	0	4.81
15% diluted to 0.1%	0.2	1.18
15% diluted to 0.1%	0.4	1.17
15% diluted to 0.1%	0.8	1.15
15% diluted to 0.1%	1	1.14
15% diluted to 0.1%	2	1.08
15% diluted to 0.1%	4	0.97

15% diluted to 0.1%	8	0.79
15% diluted to 0.1%	16	0.53
15% diluted to 0.1%	32	0.23
22% diluted to 1%	0	4.77
22% diluted to 1%	0.2	1.33
22% diluted to 1%	0.4	1.32
22% diluted to 1%	0.8	1.30
22% diluted to 1%	1	1.29
22% diluted to 1%	2	1.25
22% diluted to 1%	4	1.17
22% diluted to 1%	8	1.02
22% diluted to 1%	16	0.77
22% diluted to 1%	32	0.44

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The following data is for samples tested with PAA only.

Sample	Contact Time (min)	PAA Residual (mg·min/L)	CT dose (mg·min/L)	Average N_{exp} (MPN/100mL)
Sep. 22, AM Co = 6.97	0.00	-	0	217210
	0.75	3.46	2.48	256685
	1.50	2.72	4.85	17605
	3.50	2.69	10.64	354
	5.50	2.52	15.75	151
	8.00	2.16	21.30	126
	32.00	0.31	46.65	26
Sep. 22, PM Co = 5.79	0.00	-	0.00	210012
	1.00	3.29	3.57	186225
	2.00	2.63	6.93	28819
	4.00	2.49	13.04	481
	8.00	2.1	23.18	155
	10.00	1.82	27.37	129
	40.00	0.45	53.87	67
Sep. 24, AM Co = 6.95	0.00		0.00	1420716
	0.75	3.53	2.84	213519
	1.50	3.08	5.56	102032
	3.50	2.78	12.19	876
	5.50	2.58	18.05	357
	8.00	2.01	24.40	214
	40.00	0.6	56.71	106
Sep. 24, PM Co = 5.91	0.00	-	0.00	889812
	1.00	3.02	3.17	634671
	2.00	2.6	6.15	224841
	4.00	2.2	11.57	4148
	7.00	2	18.53	639
	10.00	1.74	24.29	549
	40.00	0.36	47.81	75

The following data is for samples tested with UV only.

Sample Date	UV irradiation time (min)	UV dose (mJ/cm^2)	Average N_{exp} (MPN/100mL)
Sep. 22, AM	0.00	0	217210
	1.16	2.5	151327
	2.32	5	32425
	4.64	10	1300
	6.96	15	212
	9.28	20	192
	18.57	40	19
Sep. 22, PM	0.00	0	210012
	1.10	2.5	79635
	2.20	5	27242
	4.40	10	941
	6.60	15	289
	8.79	20	290
	17.59	40	41
Sep. 24, AM	0.00	0	1420716
	1.14	2.5	291240
	2.27	5	64426
	4.55	10	3373
	6.82	15	598
	9.10	20	378
Sep. 24, PM	0.00	0	889812
	1.13	2.5	223162
	2.26	5	69375
	4.53	10	1853
	6.79	15	304
	9.05	20	322
	18.11	40	56

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The following data is for samples tested with UV followed by PAA.

Sample Date	UV irradiation time (min)	UV dose (mJ/cm2)	PAA Contact Time (min)	PAA Residual (mg·min/L)	CT dose (mg·min/L)	Average N_{exp} (MPN/100mL)
Sep. 22, AM Co = 6.86	4.64	10	1.50	3.38	5.49	830
	4.64	10	3.50	2.89	11.86	31
	4.64	10	5.50	2.83	17.28	22
	4.64	10	8.00	1.82	22.95	11
	6.96	15	1.50	3.41	5.35	272
	6.96	15	3.50	3.00	11.76	12
	6.96	15	5.50	2.70	17.45	67
	6.96	15	8.00	2.29	23.66	17
	9.28	20	1.50	3.72	5.76	156
	9.28	20	3.50	3.23	12.51	29
	9.28	20	5.50	2.17	18.32	25
	9.28	20	8.00	2.58	24.47	10
Sep. 22, PM Co = 6.19	4.40	10	1.50	2.96	5.89	696
	4.40	10	1.50	-	5.89	632
	4.40	10	3.50	2.22	11.20	62
	4.40	10	5.50	2.29	18.23	19
	6.60	15	1.50	2.44	5.26	260
	6.60	15	1.50	-	5.26	123
	6.60	15	3.50	2.34	10.07	33
	6.60	15	5.50	2.19	16.55	12
	6.60	15	8.00	1.64	22.23	16
	8.79	20	1.50	2.67	5.88	110

	8.79	20	1.50	-	5.88	36
	8.79	20	3.50	2.63	11.08	13
	8.79	20	5.50	1.93	17.78	10
	8.79	20	8.00	1.71	23.37	10
Sep. 24, AM Co = 7.00	4.55	10	1.50	3.47	4.97	1504
	4.55	10	1.50	-	4.97	2331
	4.55	10	3.50	3.08	10.98	121
	4.55	10	5.50	2.49	16.35	120
	4.55	10	8.00	2.44	22.28	53
	6.82	15	1.50	3.30	4.97	786
	6.82	15	1.50	-	4.97	285
	6.82	15	3.50	3.00	10.98	98
	6.82	15	5.50	2.76	16.35	50
	6.82	15	8.00	2.37	22.28	59
	9.10	20	1.50	3.53	4.97	244
	9.10	20	1.50	-	4.97	252
	9.10	20	3.50	3.17	10.98	14
	9.10	20	5.50	2.66	16.35	15
	9.10	20	8.00	2.34	22.28	15
Sep. 24, PM Co = 5.92	4.53	10	2.00	2.74	5.82	1256
	4.53	10	2.00	-	5.82	2203
	4.53	10	4.00	2.47	11.03	194
	4.53	10	7.00	2.10	17.83	118
	4.53	10	10.00	1.74	23.57	284
	6.79	15	2.00	2.67	5.73	612
	6.79	15	2.00	-	5.73	629

	6.79	15	4.00	2.45	10.85	71
	6.79	15	7.00	2.11	17.54	23
	6.79	15	10.00	1.68	23.20	141
	9.05	20	2.00	2.68	5.58	324
	9.05	20	2.00	-	5.58	209
	9.05	20	4.00	2.45	10.76	32
	9.05	20	7.00	2.35	17.84	34
	9.05	20	10.00	1.92	24.16	17

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The following data is for samples tested with PAA followed by UV.

Sample Date	PAA Contact Time (min)	PAA Residual (mg·min/L)	CT dose (mg·min/L)	UV irradiation time (min)	UV dose (mJ/cm2)	Average N_{exp} (MPN/100mL)
Sep. 22, AM Co = 6.97	1.50	2.72	4.85	4.64	10	473
	1.50	2.72	4.85	6.96	15	117
	1.50	2.72	4.85	9.28	20	53
	3.50	2.69	10.64	4.64	10	17
	3.50	2.69	10.64	6.96	15	14
	3.50	2.69	10.64	9.28	20	423
	5.50	2.52	15.75	4.64	10	18
	5.50	2.52	15.75	6.96	15	19
	5.50	2.52	15.75	9.28	20	5
	8.00	2.16	21.30	4.64	10	86
	8.00	2.16	21.30	6.96	15	47
	8.00	2.16	21.30	9.28	20	20
Sep. 22, PM Co = 5.79	2.00	2.63	6.04	4.40	10	184
	2.00	2.63	6.04	6.60	15	120
	2.00	2.63	6.04	8.79	20	41
	4.00	2.49	11.43	4.40	10	35
	4.00	2.49	11.43	6.60	15	19
	4.00	2.49	11.43	8.79	20	4
	8.00	2.1	18.45	4.40	10	22
	8.00	2.1	18.45	6.60	15	58
	8.00	2.1	18.45	8.79	20	8
	10.00	1.82	24.38	4.40	10	42

	10.00	1.82	24.38	6.60	15	13
	10.00	1.82	24.38	8.79	20	28
Sep. 24, AM 6.95	1.50	3.08	4.97	4.55	10	477
	1.50	3.08	4.97	4.55	10	326
	1.50	3.08	4.97	6.82	15	148
	1.50	3.08	4.97	9.10	20	140
	3.50	2.78	10.98	4.55	10	181
	3.50	2.78	10.98	4.55	10	207
	3.50	2.78	10.98	6.82	15	81
	3.50	2.78	10.98	9.10	20	69
	5.50	2.58	16.35	4.55	10	142
	5.50	2.58	16.35	6.82	15	192
	5.50	2.58	16.35	6.82	15	206
	5.50	2.58	16.35	9.10	20	28
	8.00	2.01	22.28	4.55	10	473
	8.00	2.01	22.28	6.82	15	139
	8.00	2.01	22.28	9.10	20	372
Sep. 24, PM Co = 5.91	2.00	2.6	5.59	4.53	10	633
	2.00	2.6	5.59	4.53	10	697
	2.00	2.6	5.59	6.79	15	176
	2.00	2.6	5.59	9.05	20	134
	4.00	2.2	10.44	4.53	10	256
	4.00	2.2	10.44	4.53	10	130
	4.00	2.2	10.44	6.79	15	74
	4.00	2.2	10.44	9.05	20	41
	7.00	2	16.51	4.53	10	90

	7.00	2	16.51	6.79	15	43
	7.00	2	16.51	6.79	15	64
	7.00	2	16.51	9.05	20	48
	10.00	1.74	21.39	4.53	10	118
	10.00	1.74	21.39	6.79	15	131

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The following data is for the simultaneous treatment with UV and PAA.

Sample Date	UV irradiation time (min)	UV dose (mJ/cm2)	PAA Contact Time (min)	PAA Residual (mg·min/L)	CT dose (mg·min/L)	Average N_{exp} (MPN/100mL)
Sep. 22, AM Co = 6.25	4.64	10	4.65	2.79	14.46	234
	4.64	10	7.00	2.48	20.30	494
	4.64	10	9.00	2.31	24.64	192
	4.64	10	12.00	1.72	30.20	216
	6.96	15	7.00	2.14	20.30	154
	6.96	15	9.00	2.26	24.64	198
	6.96	15	12.00	1.93	30.20	296
	9.28	20	9.00	1.85	24.64	272
	9.28	20	12.00	1.82	30.20	212
	4.64	10	7.00	1.81	20.30	360
	4.64	10	9.00	1.46	24.64	851
	4.64	10	12.00	1.96	30.20	230
	6.96	15	9.00	2.01	24.64	148
	6.96	15	12.00	2.00	30.20	134
	9.28	20	12.00	1.35	30.20	80
Sep. 22, PM Co = 6.32	4.40	10	4.65	2.57	13.61	230
	4.40	10	4.65	-	13.61	244
	4.40	10	7.00	2.34	19.30	40
	4.40	10	9.00	2.14	23.61	38
	4.40	10	12.00	1.93	29.27	77
	6.60	15	7.00	2.24	19.30	183
	6.60	15	9.00	1.99	23.61	82

	6.60	15	12.00	1.28	29.27	48
	8.79	20	9.00	2.13	23.61	109
	8.79	20	12.00	1.86	29.27	22
	4.40	10	7.00	2.23	19.30	84
	4.40	10	9.00	1.95	23.61	25
	4.40	10	12.00	1.62	29.27	39
	6.60	15	9.00	2.15	23.61	202
	6.60	15	12.00	1.78	29.27	63
	8.79	20	12.00	1.85	29.27	48
Sep. 24, AM Co = 6.01	4.55	10	4.65	2.41	12.80	325
	4.55	10	4.65	-	12.80	1115
	4.55	10	7.00	2.14	18.21	326
	4.55	10	9.00	2.08	22.35	203
	4.55	10	12.00	1.73	27.81	255
	6.82	15	7.00	2.21	18.21	287
	6.82	15	9.00	2.08	22.35	334
	6.82	15	12.00	1.88	27.81	134
	9.10	20	9.00	1.81	22.35	240
	9.10	20	12.00	1.52	27.81	132
	4.55	10	7.00	2.26	18.21	444
	4.55	10	9.00	2.01	22.35	209
	4.55	10	9.00	1.64	22.35	311
	4.55	10	12.00	-	27.81	305
	6.82	15	9.00	2.05	22.35	195
	6.82	15	12.00	1.55	27.81	307
	9.10	20	12.00	1.56	27.81	103

	4.53	10	4.65	2.74	14.50	271
	4.53	10	4.65	-	14.50	1817
	4.53	10	7.00	2.53	20.60	441
	4.53	10	9.00	2.31	25.23	255
	4.53	10	12.00	2.11	31.34	273
	6.79	15	7.00	2.45	20.60	513
	6.79	15	9.00	2.38	25.23	560
Sep. 24, PM Co = 6.25	6.79	15	12.00	1.93	31.34	895
	9.05	20	9.00	2.14	25.23	154
	9.05	20	12.00	1.92	31.34	262
	4.53	10	7.00	2.39	20.60	414
	4.53	10	9.00	2.15	25.23	977
	4.53	10	9.00	-	25.23	828
	4.53	10	12.00	1.87	31.34	256
	6.79	15	9.00	2.11	25.23	700
	6.79	15	12.00	1.79	31.34	711
	9.05	20	12.00	1.54	31.34	161

Appendix B

Additional Testing for Disinfection – Contract 28231 at the T.E. Maxson Wastewater Treatment Plant

Technical Memorandum

To: *Scott Morgan, P.E.*
Mike Brower, Plant Manager
City of Memphis, Environmental Engineering Department

From: *Kati Bell, Ph.D., PE, BCEE*
Joshua E. Goldman, Ph.D.
Sarah A. Stewart, PE

Date: *April 28, 2015*

Subject: *Additional Testing for Disinfection - Contract 28231*
at the T.E. Maxson Wastewater Treatment Plant

This technical memorandum provides information and guidelines on the operation and sampling protocols for the peracetic acid (PAA) parallel pipe reactor pilot to be conducted at the T.E. Maxson wastewater treatment plant (Maxson WWTP). PAA piloting was previously conducted at the Maxson WWTP in 2013; during the time of the initial pilot testing, construction of the new fine bar screens was nearing completion. Since that time, the facility has observed notable improvements in plant performance. Additionally, there has been a significant change in the plant influent loading due to a reduction in discharges from one of the major industrial users. Considering these factors, coupled with the potential benefits of aligning disinfection technologies between the Maxson WWTP and the Stiles WWTP, it is useful to conduct a brief pilot study to determine whether these changes have impacted the UV and PAA design doses.

Objectives

The key objectives of the additional testing to be conducted are aimed at supplementing the bench and pilot testing that have previously been conducted at the Maxson WWTP. In order to confirm the results of previous testing, in light of the recent changes at the facility, the following objectives will be addressed with the current testing with respect to meeting limits for Eschercia coli (E. coli) as outlined in the current draft National Pollutant Discharge Elimination System (NPDES) permit:

- Confirm the UV disinfection design dose to support estimates of capital and operating costs
- Refine the design criteria for PAA disinfection to meet disinfection limits
    - Determine the kinetic model parameters to predict PAA disinfection efficacy across a range of doses and contact times; this information will be used to establish the sizing for a contact basin to support calculation of associated capital costs

- Determine the design dose for average conditions to support calculation of associated operating costs

UV Disinfection

In order to size a UV disinfection system, the disinfection dose must be established. For an existing facility with effluent available, the most accurate dose sizing can be accomplished using site-specific information for the target organism, here *E. coli*, based on its UV dose-response. This data is developed using a collimated beam test, which allows a sample to be exposed to UV irradiation at increasing doses, with measurement of the resulting bacteria concentration at each dose. The data is then analyzed to determine the target organism sensitivity (D_L) by evaluating the log inactivation rate per dose. The D_L is then used along with data on undisinfected effluent bacteria concentrations to establish target inactivation rates for design. The inactivation rates are multiplied by the site-specific D_L, and safety factors that represent the level of variability observed in multiple collimated beam studies to set the design dose. UV disinfection equipment systems are sized based on a bioassay of one or more surrogate organisms. In order to account for potential site-specific water quality effects on the disinfection of the surrogate organism, three collimated beam samples will also be run for MS2 (male-specific [F+] bacteriophage).

In addition to defining the UV dose through collimated beam testing, it is also important to characterize the effluent total suspended solids (TSS) with respect to its potential effects on UV disinfection. While the concentration of suspended solids (total weight measurement) is typically used to evaluate the potential performance of a UV disinfection system, correlations between suspended solids concentrations and UV performance are sometimes inconsistent. Thus, a great deal of research has been conducted on the impact of suspended solids on UV disinfection. Suspended solids cause the observed effects (i.e., decreased disinfection rate and tailing) by interfering with UV disinfection in three ways: (1) by scattering or absorbing light, (2) by shading organisms, and (3) by shielding embedded organisms. In these ways, particles can interfere with UV disinfection as shown in **Figure 1**.

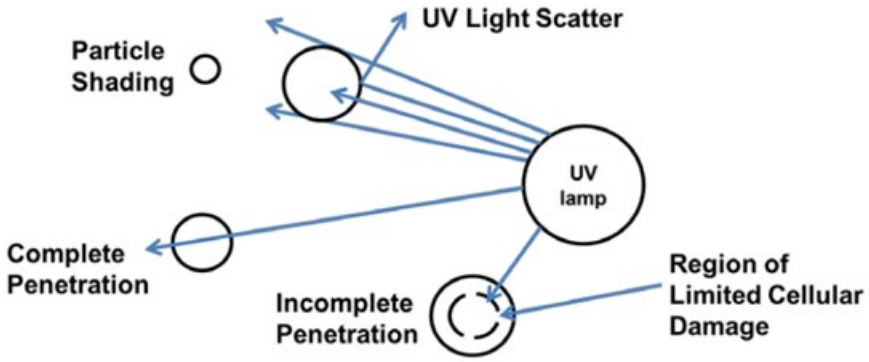


Figure 1. Possible Interactions between UV Light and Wastewater Particles

A number of researchers have concluded that UV light fully penetrates through particles smaller than 10 µm, but not at all through particles larger than 40 µm, even at high UV doses. Thus, 10 – 20 µm is a critical size, or the lower limit size for shielding microorganisms. The extent to which bacteria associate with particles appears to vary widely and is site specific; factors that affect bacterial association with particles include particle size, the nature of the particles, treatment type, and sludge age. Several studies have demonstrated that the protection provided by particles increases with particle size and both the dose and the level of survival at which the dose-response curve begins to tail decreases with a decrease in the size of particles. As a result, when conducting collimated beam studies to confirm design dose for a wastewater UV disinfection project, it is also recommended that a particle size analysis also be conducted. Once particle size distribution data has been collected, a project engineer will need to review the data to determine if the amount of TSS particles in the > 20 micron size fraction is of concern. If there is a significant fraction of > 20 micron particles, the project engineer will need to coordinate with the UV equipment manufacturer to adjust the delivered dose to account for the presence of these large particles.

UV Disinfection Testing Protocol

During this additional testing period, secondary effluent samples will be collected and shipped overnight on ice to an outside laboratory for collimated beam and particle size distribution analysis. Sample kits will be provided by the laboratory. For each collimated beam sample, 1.5 liters of secondary effluent will be collected in pre-cleaned bottles. For particle size distribution analysis (PSD), 500 milliliters of secondary effluent will be collected in pre-cleaned bottles. Two to three drops of bleach (provided in sample kit) will be added to the PSD samples for preservation. This prevents solids characteristics changing prior to analysis.

UV Disinfection Testing Schedule

Samples will be collected three times per week for four weeks for a total of 12 collections; the anticipated sample collection schedule is provided in **Table 1**.

Table 1 Collimated Beam and PSD Sampling Schedule

Date(s)	Samples Collected
May 4th, 11th, 18th ,	Collimated Beam (E. coli and MS2), Particle Size Distribution Analysis
May 5th, 6th, 12th, 13th, 19th, 20th, 25th, 26th, 27th	Collimated Beam (E. coli), Particle Size Distribution Analysis

PAA Disinfection

Unlike chlorine, PAA does not have well documented requirements for design, thus, it is critical to understand the disinfection kinetics associated with this process to provide appropriate design criteria for implementation. The most import factors for design of a PAA system are the contact time and design dose. For chlorine disinfection, a "CT" (residual concentration times contact time) approach has been traditionally used. However, this approach is not adequate in assessing the effectiveness of PAA disinfection because of differences in chemical half-lives. As a result, it is necessary to capture the PAA reaction kinetics and utilize it in a microbial inactivation model to describe the inactivation process taking place. There are a number of models that have been developed to address this effect and among the published models, Hom's model is the most widely used to account for deviations from the Chick-Watson formula:

$$\log\left(\frac{N}{N_0}\right) = -kC^n t^m$$

In Hom's model, *m* is used to account for the shorter half-life of PAA. The model has been validated in several studies, showing that Hom's model is the most appropriate for describing PAA disinfection of secondary wastewater effluent for coliform organisms (Rossi et al., 2007[1]; Azzellino et al., 2011[2]). Data will be collected during the pilot study that will support analysis using this model to make recommendations on the design dose and contact times for possible implementation of PAA at the Maxson WWTP.

[1] Rossi S., Antonelli M., Mezzanotte V., Nurizzo C. (2007). Peracetic acid disinfection: a feasible alternative to wastewater chlorination. *Water Environment Research*, 79 (4): 341-350.

[2] Azzellino A., Antonelli M., Canziani R., Malpei F., Marinetti M., Nurizzo C. (2011). Multivariate modeling of disinfection kinetics: A comparison among three different disinfectants. *Desalination and Water Treatment*, 29 (1/3): 128-139.

PAA Disinfection Testing Protocol

A mobile pilot reactor, supplied by PeroxyChem (**Figures 2** and **3**), will be installed at the Maxson WWTP near the final clarifiers. Test conditions for the pilot reactor are outlined in **Table 2**.

Figures 2 and 3 - Pipe Reactor Photos

Table 2 Testing Conditions

Design Parameter	Condition
Chemical Information	VigorOx® WWT II
	MSDS 79-21-0-27
	15% Peracetic Acid by Weight
Contact Time	20 min
PAA Dose Range	7-12 mg/L (as active ingredient)
Pipe Reactor Flow Rate	~25 gpm through the reactor

PeroxyChem will provide the pipe reactor, the PAA, chemical storage and containment systems, chemical feed pump skid, piping, valves, appurtenances, and tubing for the PAA feed system to the pipe reactor. Layout drawings of the PeroxyChem equipment are included in **Appendix A**. The pilot reactor arrived on site and is being installed the week of April 27th. The supply water to the PAA reactor will be effluent pumped from the final clarifiers to the PAA pilot; the pilot discharge will be routed back to the final clarifiers. Pumping capabilities and piping are provided by Peroxychem. The Material Safety Data Sheet (MSDS) for the PAA used in this pilot test is included in **Appendix B**.

Safety and operational training will be conducted by PeroxyChem for CDM Smith and T.E. Maxson personnel. Operation of the pilot will be performed by CDM Smith personnel during the course of the pilot; however CDM Smith staff will not be onsite 24-hours per day, 7-days per week, thus in the event that an issue arises with the pilot, Maxson WWTP staff will be trained on pilot-shut down procedures.

Pilot System Testing

Following the 2013 pilot study, a PAA dose of 13 mg/L was recommended for use at full scale. Kinetics are more favorable at the pilot scale, and data from the pilot (**Figure 4**) indicate that a dose of 10 mg/L was required to reduce the *E. coli* concentration to 126 colony forming units (cfu)/100 mL. A dose matrix was developed (**Table 3**) based on historical data from the pilot that was conducted in 2013 with the anticipation that recent changes at the facility that have improved effluent water quality may result in a lower required dose.

A bench scale test was performed the week of April 20th to verify the dose ranges identified in the previous pilot early in the pilot schedule. The PAA doses in the dose matrix may be modified during the testing, depending on the bench scale test results, which are anticipated by May 1st.

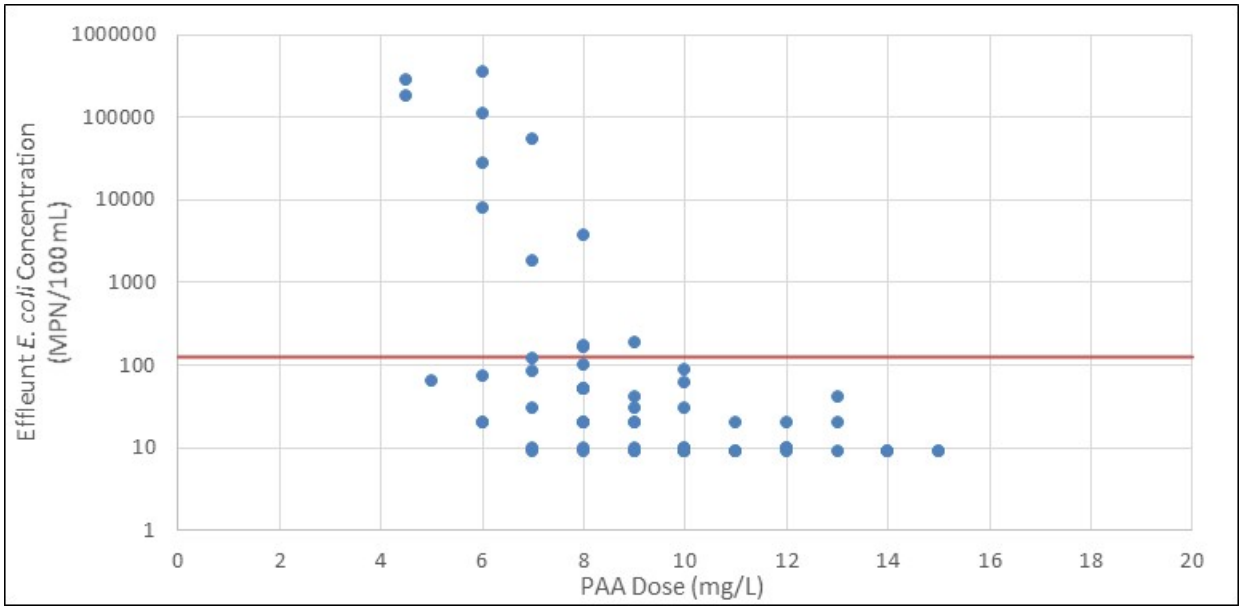


Figure 4 2013 PAA Pilot Data shown with Monthly Geometric Mean Limit of 126 cfu/100 mL

Table 3 Dose Matrix

Week	PAA Dose (mg/L)
1	7
2	8
3	9
4	10
5	11
6	12

Experiments will be conducted four times per day, Monday through Friday. The sampling matrix (**Table 4**) was developed to collect sufficient data for application of the Hom's model, to correlate water quality parameters such as TSS and apparent color with disinfection efficacy.

Table 4 Sampling Plan

Analysis	Measurement Location	Secondary Effluent (Control)	Sample Ports 1,2,3,4,5	Sample Port 6	Total[1]
TSS (mg/L)	ETC Lab	1x Daily		--	30
pH (SU)	Field	4x Daily	1x Daily	4x Daily	390[2]
Unfiltered UVT (%)	ETC Lab	1x Daily		1x Daily	60
Apparent Color (PtCo)	ETC Lab	1x Daily		1x Daily	60
Residual PAA (mg/L)	Field	4x Daily	1x Daily	4x Daily	390
E. coli (MPN/100 mL)	ETC Lab	4x Daily	1x Daily	4x Daily	390
Nitrite (mg/L)	ETC Lab	1x Daily		1x Daily	60

Notes:

1. Totals are based upon a pilot test duration of 6 weeks.
2. Total number of pH, PAA residual, and E. coli residual measurement were calculated as follows: 30 days of testing multiplied by 13 tests per day (4 at control port, 4 at port 6, 1 each at ports 1-5)

CDM Smith/Powers Hill staff will collect the samples identified in **Table 4**. A full kinetic test, in which samples are collected from every port on the reactor, will be performed once per day. The other three tests will include influent and effluent samples only. This scheme allows for multiple kinetic tests at each PAA dose, to provide data for Hom's model while minimizing sampling and analysis costs. Field parameters will be measured immediately and laboratory samples will be delivered on a daily basis to ETC Laboratory for analysis. PAA residual concentration will be measured using a hand held analyzer provided by PeroxyChem, and field pH will be measured using a meter provided by CDM Smith.

Although the dose matrix and sampling plan indicate a six week testing period, the pilot may be completed in four weeks if sufficient data is collected to support development of Hom's model. The

dose matrix is designed to start at a low PAA dose and increase weekly. The pilot schedule may be reduced if the dose resulting in complete inactivation of *E. coli* is reached before the sixth week.

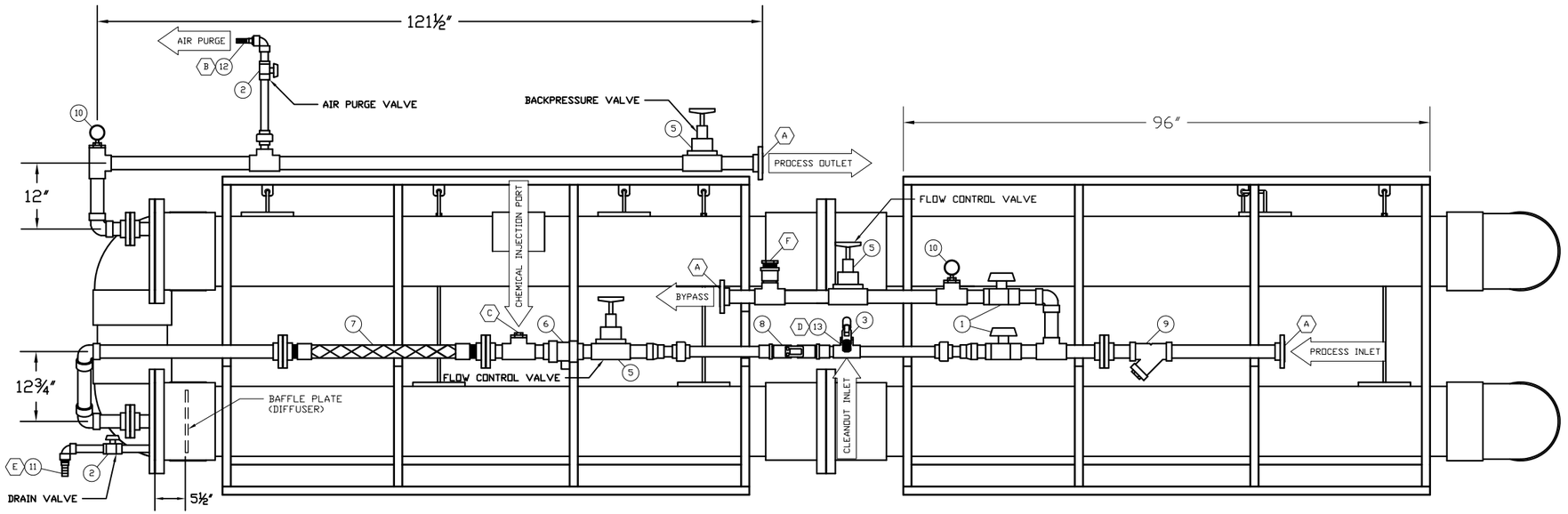
Post Pilot Testing Activities

Following completion of the testing, PeroxyChem will disassemble and remove the pilot reactor, the chemical feed skid, any remaining PAA, and the PAA storage and containment system from the Maxson WWTP.

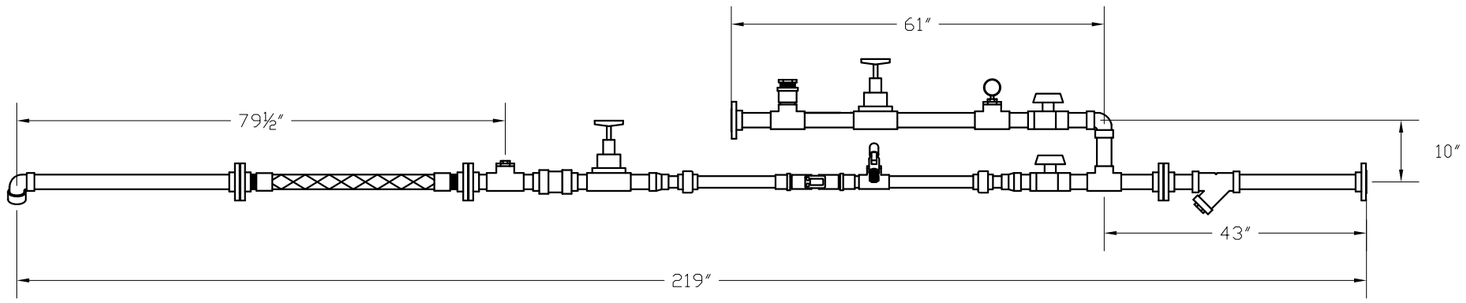
CDM Smith will update the original draft PAA pilot technical memorandum to include findings based on the results collected during this testing. The technical memorandum will summarize pilot data and results, including a recommended design dose and updated costs for both UV and PAA disinfection to meet the discharge permit limits.

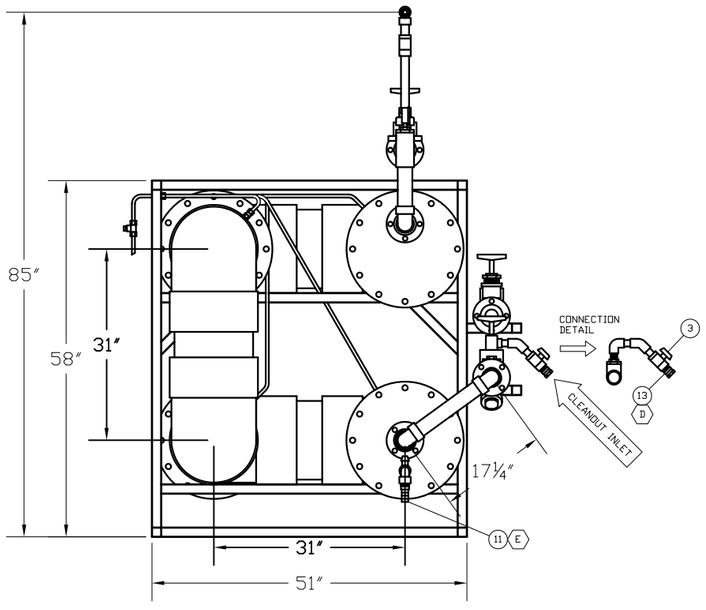
Appendix A

PeroxyChem Equipment Drawings



FRONT ELEVATION





END VIEW

BILL OF MATERIALS

1. BALL VALVE, 2″ SW, PVC, EPDM SEAL (2)
2. BALL VALVE, 1″ SW, PVC, EPDM SEAL (2)
3. BALL VALVE, ¾″ SW, PVC, EPDM SEAL (1)
4. BALL VALVE, ½″ TUBE FITTING, 316 SS, CHEMRAZ BUSHING AND PACKING (5)
5. GLOBE VALVE, 2″ SW, PVC, EPDM PACKING, PP DISC (3)
6. CHECK VALVE, 2″ FNPT, PVC, FLUOROELASTOMER SEAL (1)
7. STATIC MIXER, 12 BLADES, 35″ LONG, 2″ MNPT, PVC (1)
8. TURBINE FLOWMETER/TOTALIZER, 1½″ FNPT, PVC, 316 SS SEAL (1)
9. Y-STRAINER, 1/32″ PERFORATIONS, 2″ SW, PVC, FLUOROELASTOMER SEAL (1)
10. PRESSURE GAUGE, 0-100 PSI, , ¼″ MNPT, 316L SS (3)
11. HOSE ADAPTER, 1″ MNPT x 1″ HOSE ID, BLACK PP (1)
12. HOSE ADAPTER, ¾″ MNPT x ¾″ OD HOSE, 316 SS (1)
13. HOSE CONNECTION, ¾″ MNPT x ¾″ GARDEN HOSE, BRASS (1)

NOTE: DISTANCE FROM CHEMICAL INJECTION PORT TO INLET OF PIPE REACTOR (12″ PIPE) IS 108″ (EXACTLY 9′).

NOZZLE SCHEDULE

A. FLANGE, 2″ 150 LB RF, PVC (3)
B. ¾″ ID HOSE, 316 SS
C. ¼″ FNPT, 316 SS
D. GARDEN HOSE CONNECTION, ¾″, BRASS
E. 1″ ID HOSE, PP
F. PLUG, 2″ MNPT, PVC

MARK		DATE	BY	CHK.

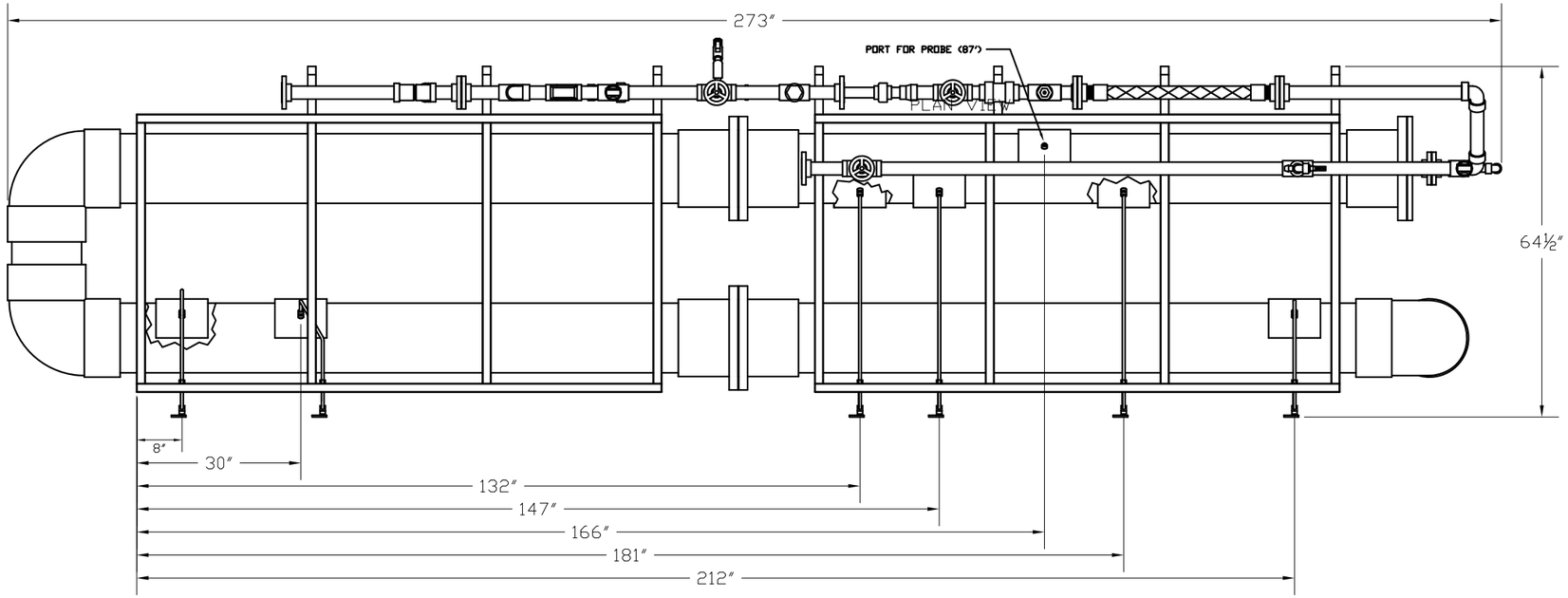
REVISIONS

FMC Corporation
Technical Service Engineering
Box 845, Buffalo, New York 14240

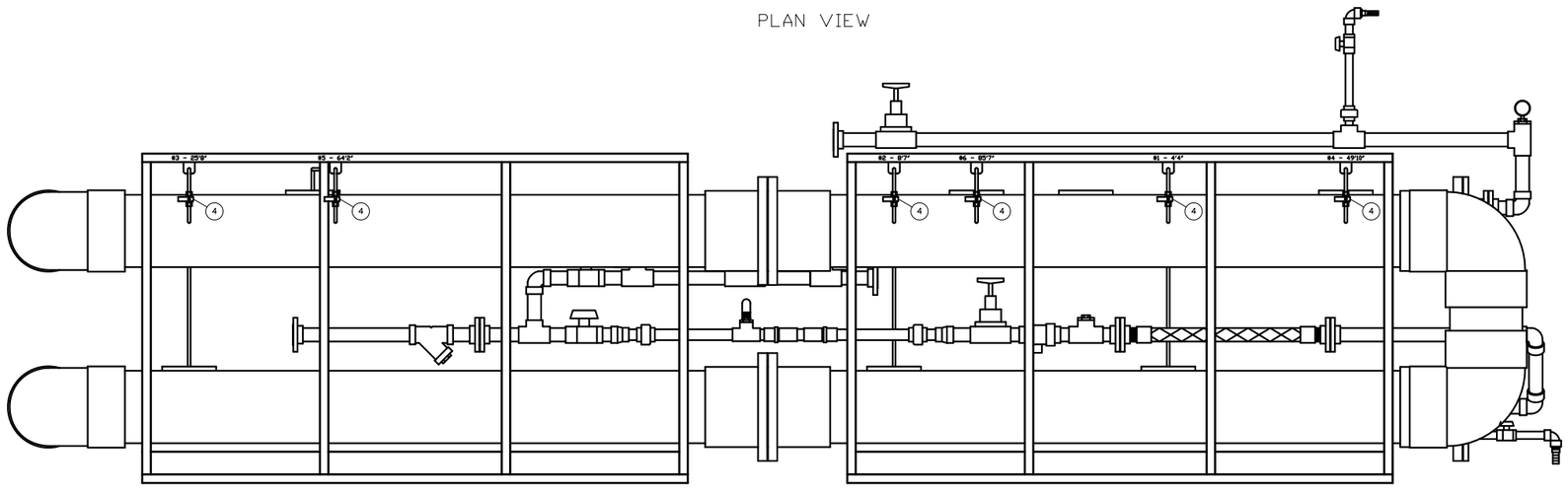
REFERENCE DRAWINGS	FEED_AND_DISCHARGE_PIPING	
BOM_F2404706	FMC_PIPE_REACTOR	
XXXX	SHEET_1_OF_2	
XXXX	XXXX	
XXXX	XXXX	
XXXX	DRAWN: MJM	DATE: 1/13/2014
XXXX	SCALE: XXX	ENGINEER: MJM

DRAWING NO. F2404706

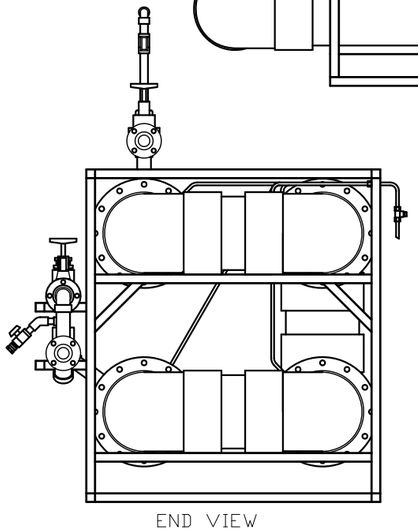
REV. 0



PLAN VIEW

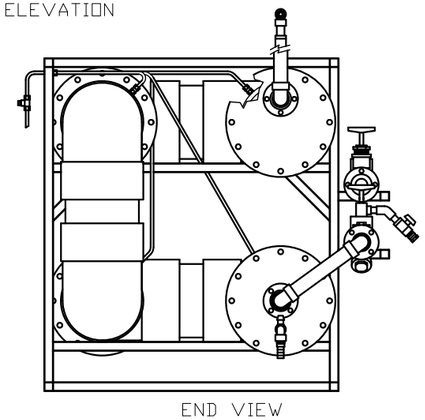


BACK ELEVATION



END VIEW

NOTE: DIMENSIONS ABOVE REPRESENT THE FOOTPRINT OF THE PIPE REACTOR AND LOCATIONS OF SAMPLE PORTS.



END VIEW

MARK		DATE	BY	CHK.

REVISIONS

FMC Corporation
Technical Service Engineering
Box 845, Buffalo, New York 14240

REFERENCE DRAWINGS	FEED_AND_DISCHARGE_PIPING	
BOM_F2404706	FMC_PIPE_REACTOR	
XXXX	SHEET_2_OF_2	
XXXX	XXXX	
XXXX	XXXX	
XXXX	DRAWN: MJM	DATE: 1/13/2014
XXXX	SCALE: XXX	ENGINEER: MJM

DRAWING NO. F2404706

REV. 0

Appendix B

PAA Material Safety Data Sheets

MATERIAL SAFETY DATA SHEET

VigorOx® WWT II

MSDS #: 79-21-0-27
Revision date: 2013-02-11
Version 1.01

This MSDS has been prepared to meet U.S. OSHA Hazard Communication Standard 29 CFR 1910.1200
And Canadian Workplace Hazardous Materials Information System (WHMIS) requirements.

1. PRODUCT AND COMPANY IDENTIFICATION

Product Name **VigorOx® WWT II**

Synonyms Peroxyacetic Acid Solution; Peracetic Acid Solution; Ethanperoxoic acid

EPA Registration Number 65402-8
Recommended Use: Wastewater and sewage effluent disinfection; PeroxyChem acquired the EPA product registration from FMC

Manufacturer/Supplier

PeroxyChem LLC
2005 Market Street
Suite 3200
Philadelphia, PA 19103
Phone: +1 267/ 422-2400 (General Information)
E-Mail: sdsinfo@peroxychem.com

Emergency telephone number

For leak, fire, spill or accident emergencies, call:
1 800 / 424 9300 (CHEMTREC - U.S.A.)
1 703 / 527 3887 (CHEMTREC - Collect - All Other Countries)
1 303/ 389-1409 (Medical - U.S. - Call Collect)

2. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

Clear liquid with a sharp, pungent, vinegar-like odor
oxidizer
Contact with combustible material may cause fire
Liquid and mist are corrosive
Direct contact can cause irreversible damage to eyes and skin

Potential Health Effects

Eyes Corrosive to the eyes and may cause severe damage including blindness.
Skin Corrosive to skin.
Inhalation Vapor/mist will irritate nose, throat and lungs.
Ingestion Harmful if swallowed.

Chronic toxicity Repeated inhalation of the mist may cause inflammation of the upper respiratory tract, chronic bronchitis and etching of the dental enamel.

Environmental Hazard Very toxic to aquatic organisms.

3. COMPOSITION/INFORMATION ON INGREDIENTS

Ingredients

Chemical name	CAS-No	Weight %
Water	7732-18-5	45
Hydrogen Peroxide	7722-84-1	23
Acetic Acid	64-19-7	16
Peracetic Acid	79-21-0	15
Sulfuric Acid	7664-93-9	1

4. FIRST AID MEASURES

Eye Contact Immediately flush with plenty of water. After initial flushing, remove any contact lenses and continue flushing for at least 15 minutes. Immediate medical attention is required.

Skin Contact Wash off immediately with soap and plenty of water for at least 15 minutes while removing all contaminated clothing and shoes. Immediate medical attention is required.

Inhalation Move to fresh air. If breathing is irregular or stopped, administer artificial respiration. Administer oxygen if breathing is difficult. Call a poison control center or doctor for further treatment advice.

Ingestion Immediate medical attention is required. Rinse mouth. Do NOT induce vomiting. Drink 1 or 2 glasses of water. Never give anything by mouth to an unconscious person. If swallowed, do not induce vomiting - seek medical advice.

Indication of immediate medical attention and special treatment needed, if necessary This product can be corrosive to skin, eyes, and mucous membranes. Consideration should be given to careful endoscopy as stomach or esophageal burns, perforations or strictures may occur. Careful gastric lavage with an endotracheal tube in place should be considered. Observations may be warranted. Treatment is controlled removal of exposure followed by symptomatic and supportive care.

5. FIRE-FIGHTING MEASURES

Flammable properties Substance does not burn but will support combustion.

Flash point 68 °C Closed cup

Suitable Extinguishing Media Water. Cool containers with flooding quantities of water until well after fire is out.

Unsuitable extinguishing media Chemical type extinguishers are not effective with peracetic acid or hydrogen peroxide.

Uniform Fire Code Organic Peroxide: Class 4--Liquid

Explosion data

Sensitivity to Mechanical Impact Not Available
Sensitivity to Static Discharge Not Available

Specific Hazards Arising from the Chemical Decomposes under fire conditions to release oxygen that intensifies the fire.

Protective equipment and precautions for firefighters Wear self-contained breathing apparatus and protective suit. Fight fire from maximum distance or use unmanned hose holders or monitor nozzles.

NFPA	Health Hazards 3	Flammability 1	Stability 2	Special Hazards OX

6. ACCIDENTAL RELEASE MEASURES

Personal Precautions Keep people away from and upwind of spill/leak. Avoid contact with the skin and the eyes. Use personal protective equipment. For personal protection see section 8.

Methods for Containment Control runoff and isolate discharged material for proper disposal. Do not allow material to enter storm or sanitary sewer system

Methods for cleaning up Combustible materials exposed to hydrogen peroxide should be immediately submerged in or rinsed with large amounts of water to ensure that all hydrogen peroxide is removed. Residual hydrogen peroxide that is allowed to dry (upon evaporation hydrogen peroxide can concentrate) on organic materials such as paper, fabrics, cotton, leather, wood or other combustibles can cause the material to ignite and result in fire.

7. HANDLING AND STORAGE

Handling Handle product only in closed system or provide appropriate exhaust ventilation.
Drums - Empty as thoroughly as possible. Triple rinse drums before disposal. Avoid contamination; impurities accelerate decomposition. Never return product to original container.
IBCs (Tote) - IBCs should be emptied as thoroughly as possible and recycled without rinsing.

Storage Keep in a dry, cool and well-ventilated place. Do not store near combustible materials. Keep away from heat and sources of ignition i.e., steam pipes, radiant heaters, hot air vents or welding sparks. Keep at temperatures below 30°C. Containers must be vented. Use first in, first out storage system.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Exposure Guidelines .

Chemical name	ACGIH TLV	OSHA PEL	NIOSH	Mexico
Hydrogen Peroxide 7722-84-1	TWA: 1 ppm	TWA: 1 ppm TWA: 1.4 mg/m³	IDLH: 75 ppm TWA: 1 ppm TWA: 1.4 mg/m³	Mexico: TWA 1 ppm Mexico: TWA 1.5 mg/m³ Mexico: STEL 2 ppm Mexico: STEL 3 mg/m³
Sulfuric Acid 7664-93-9	TWA: 0.2 mg/m³	TWA: 1 mg/m³	IDLH: 15 mg/m³ TWA: 1 mg/m³	Mexico: TWA 1 mg/m³
Acetic Acid 64-19-7	STEL 15 ppm TWA: 10 ppm	TWA: 10 ppm TWA: 25 mg/m³	IDLH: 50 ppm TWA: 10 ppm TWA: 25 mg/m³ STEL: 15 ppm STEL: 37 mg/m³	Mexico: TWA 10 ppm Mexico: TWA 25 mg/m³ Mexico: STEL 15 ppm Mexico: STEL 37 mg/m³
Peracetic Acid 79-21-0	STEL 0.4 ppm			

Chemical name	British Columbia	Quebec	Ontario TWAEV	Alberta
Hydrogen Peroxide 7722-84-1	TWA: 1 ppm	TWA: 1 ppm TWA: 1.4 mg/m³	TWA: 1 ppm	TWA: 1 ppm TWA: 1.4 mg/m³
Acetic Acid 64-19-7	TWA: 10 ppm STEL: 15 ppm	TWA: 10 ppm TWA: 25 mg/m³ STEL: 15 ppm STEL: 37 mg/m³	TWA: 10 ppm STEL: 15 ppm	TWA: 10 ppm TWA: 25 mg/m³ STEL: 15 ppm STEL: 37 mg/m³
Sulfuric Acid 7664-93-9	TWA: 0.2 mg/m³	TWA: 1 mg/m³ STEL: 3 mg/m³	TWA: 0.2 mg/m³	TWA: 1 mg/m³ STEL: 3 mg/m³

Occupational exposure controls

Engineering measures Apply technical measures to comply with the occupational exposure limits. When working in confined spaces (tanks, containers, etc.), ensure that there is a supply of air suitable for breathing and wear the recommended equipment.

General information These recommendations apply to the product as supplied

Respiratory Protection	When workers are facing concentrations above the exposure limit they must use appropriate certified respirators. Wear a positive-pressure supplied-air respirator with full facepiece.
Eye/Face Protection	Chemical resistant goggles must be worn. If splashes are likely to occur, wear: Face-shield.
Skin and Body Protection	Rubber or neoprene footwear. Impervious clothing materials such as rubber, neoprene, nitrile or polyvinyl chloride. Wear liquid proof rubber or neoprene gloves Hydrogen peroxide is an ingredient in this product; completely submerge hydrogen peroxide contaminated clothing or other materials in water prior to drying. Residual hydrogen peroxide, if allowed to dry on combustible materials such as paper, fabrics, leather or wood can cause the material to ignite and result in a fire
Hand Protection	Rubber/latex/neoprene or other suitable chemical resistant gloves. Wash the outside of gloves with soap and water prior to removal. Inspect regularly for leaks. Please observe the instructions regarding permeability and breakthrough time which are provided by the supplier of the gloves. Also take into consideration the specific local conditions under which the product is used, such as the danger of cuts, abrasion and the contact time. If used in solution, or mixed with other substances, and under conditions which differ from EN 374, contact the supplier of the EC approved gloves
Other Protective Equipment	Ensure that eyewash stations and safety showers are close to the workstation location.
Hygiene measures	When using, do not eat, drink or smoke. Wear suitable gloves and eye/face protection Wash hands before breaks and at the end of workday. Wash hands with water as a precaution Regular cleaning of equipment, work area and clothing is recommended Avoid breathing vapors, mist or gas.

9. PHYSICAL AND CHEMICAL PROPERTIES

Information on basic physical and chemical properties

Appearance	Clear, colorless liquid
Physical State	Liquid
Odor	stinging, Pungent, vinegar-like
pH	< 1 (1% solution = 2-3 @ 25°C)
Melting Point/Range	Not applicable
Freezing Point	-49 °C
Boiling Point/Range	108 °C
Flash point	68 °C Closed cup
Evaporation Rate	>1 (BuAc = 1)
Flammable properties	Substance does not burn but will support combustion
Oxidizing properties	Strong oxidizer
Vapor pressure	20 mm Hg at 25ºC
Specific gravity	1.16 @ 20°C (H20 = 1)
Bulk Density	Not applicable
Water solubility	completely soluble
Decomposition temperature	> 55 °C (SADT)
Autoignition temperature	270 °C

10. STABILITY AND REACTIVITY

Stability	Stable under recommended storage conditions. Decomposes on heating.
Conditions to Avoid	Heat, flames and sparks; Combustibles such as paper and wood; Temperatures above 30°C.
Materials to avoid	Oxidizing agents; Strong reducing agents; Combustible materials; Heavy metals.
Hazardous Decomposition Products	Oxygen which supports combustion.
Hazardous polymerization	Hazardous polymerization does not occur.

11. TOXICOLOGICAL INFORMATION

Acute Effects

Eye irritation Severely irritating, corrosive (rabbit)

Skin irritation Severely irritating, corrosive (rabbit)

LD50 Oral LD50 Rat = 50 -500 mg/kg/bw (35% Peracetic acid)
LD50 rat = 1026-1780 mg/kg/bw (15% Peracetic acid)
LD50 rat = 185-3622 mg/kg/bw (2.6-6.11% Peracetic acid)

LD50 Dermal LD50 Rat = 1957 mg/kg/bw (15% Peracetic acid)
LD50 rat = 1147 mg/kg/bw (5% Peracetic acid)
LD50 rat = >2000 mg/kg/bw (Peracetic acid 0.15%-0.89%)

LC50 Inhalation LC50 (4-hr) Rat = 76-189 mg/m^3 (15% Peracetic acid)
LC50 (4-h) rat = 204 mg/m^3 (5% Peracetic acid)

Sensitization Did not cause sensitization on laboratory animals

Chronic toxicity

Chronic toxicity Repeated inhalation of the mist may cause inflammation of the upper respiratory tract, chronic bronchitis and etching of the dental enamel.

Carcinogenicity Did not show carcinogenic effects in animal experiments Topical applications do not produce skin tumors Not recognized as carcinogenic by Research Agencies (IARC, NTP, OSHA, ACGIH)

Chemical name	ACGIH	IARC	NTP	OSHA
Hydrogen Peroxide	A3	Group 3		
Sulfuric Acid	A2	Group 1		X

Legend:

IARC (International Agency for Research on Cancer)
Group 1 - Carcinogenic to Humans
OSHA (Occupational Safety and Health Administration of the US Department of Labor)
X - Present

12. ECOLOGICAL INFORMATION

Ecotoxicity

Peracetic Acid (79-21-0)

Active Ingredient(s)	Duration	Species	Value	Units
Peracetic Acid 15%	96 h LC50	Oncorhynchus mykiss (rainbow trout)	0.53	mg/L
Peracetic Acid 5%	96 h LC50	Bluegill sunfish	1.1	mg/L
Peracetic Acid	33 d NOEC	Brachydanio rerio	0.00225	mg/L
Peracetic Acid 5%	96 h LC50	Oncorhynchus mykiss (rainbow trout)	1.6	mg/L
Peracetic Acid 5%	48 h EC50	Daphnia magna	0.73	mg/L
Peracetic Acid 12.5%	48 h EC50	Mytilus sdulis	0.27	mg/L
Peracetic Acid 15%	21 d NOEC	Daphnia magna	0.05	mg/L
Peracetic Acid 5%	72 h EC50	Selenastrum capricornutum	0.16	mg/L
Peracetic Acid 5%	120 h EC50	Selenastrum capricornutum	0.18	mg/L
Peracetic Acid 5%	72 h NOEC	Selenastrum capricornutum	0.061	mg/L
Peracetic Acid	3 h EC50	Respiration inhibition test (OECD 209)	5.1	mg/L

Persistence and degradability Peracetic acid is completely miscible with water. Aqueous solutions of peracetic acid hydrolyze to acetic acid and hydrogen peroxide. Product is biodegradable

Bioaccumulation Based on its low octanol-water partition coefficient and its rapid degradation in the environment, this product is not bioaccumuable.

Mobility Peracetic acid released in the environment will partition almost exclusively (>99%) to the water compartment. Only a minor part (<1%) will remain in the atmosphere, where it is expected to undergo rapid decomposition with a half life of 22 minutes. The fate of peracetic acid in the environment is mainly determined by its degradation.

Other Adverse Effects None known

13. DISPOSAL CONSIDERATIONS

Waste disposal methods This material, as supplied, is a hazardous waste according to federal regulations (40 CFR 261). It must undergo special treatment, e.g. at suitable disposal site, to comply with local regulations. Dispose of contents/container in accordance with local regulation.

RCRA D Waste Code D001 (ignitable). D002 (corrosive).

Contaminated Packaging Non-returnable containers that held this material should be cleaned by triple-rinsing prior to recycle or disposal. Empty containers should be taken to an approved waste handling site for recycling or disposal.

US EPA Waste Number D002

14. TRANSPORT INFORMATION

DOT

UN/ID no UN3109
Proper Shipping Name ORGANIC PEROXIDE TYPE F, LIQUID (<=17% Peracetic Acid with <=26% Hydrogen Peroxide)

Hazard class	5.2
Subsidiary class	8
Packing Group	II

TDG

UN/ID no	UN3109
Proper Shipping Name	ORGANIC PEROXIDE TYPE F, LIQUID (<=17% Peracetic Acid with <=26% Hydrogen Peroxide)
Hazard class	5.2
Subsidiary class	8
Packing Group	II
Description	UN3109, Organic Peroxide Type F, Liquid (<=17% Peracetic Acid with <=26% Hydrogen Peroxide), 5.2 (8), PG II

ICAO/IATA

UN/ID no	UN3109
Proper Shipping Name	ORGANIC PEROXIDE TYPE F, LIQUID (<=17% Peracetic Acid with <=26% Hydrogen Peroxide)
Hazard class	5.2
Subsidiary Hazard Class	8
Packing Group	II
Special Provisions	Venting of packages is not permitted for air transport.
Description	UN3109, Organic Peroxide Type F, Liquid (<=17% Peracetic Acid with <=26% Hydrogen Peroxide), 5.2 (8), PG II

IMDG/IMO

UN/ID no	UN3109
Proper Shipping Name	ORGANIC PEROXIDE TYPE F, LIQUID (<=17% Peracetic Acid with <=26% Hydrogen Peroxide)
Hazard class	5.2
Subsidiary Hazard Class	8
Packing Group	II
Description	UN3109, Organic Peroxide Type F, Liquid (<=17% Peracetic Acid with <=26% Hydrogen Peroxide), 5.2 (8), PG II

15. REGULATORY INFORMATION

International Inventories

TSCA (United States)	Complies
DSL (Canada)	Complies
NDSL (Canada)	Complies
EINECS/ELINCS (Europe)	Complies
ENCS (Japan)	Complies
China (IECSC)	Complies
KECL (Korea)	Complies
PICCS (Philippines)	Complies
AICS (Australia)	Complies
NZIoC (New Zealand)	Complies

U.S. Federal Regulations

SARA 313

Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA). This product does not contain any chemicals which are subject to the reporting requirements of the Act and Title 40 of the Code of Federal Regulations, Part 372

SARA 311/312 Hazard Categories

Acute health hazard	Yes
Chronic health hazard	No

Fire hazard	Yes
Sudden release of pressure hazard	No
Reactive Hazard	Yes

CERCLA

Chemical name	Hazardous Substances RQs	Extremely Hazardous Substances RQs
Hydrogen Peroxide		1000 lb
Acetic Acid	5000 lb	
Peracetic Acid		500 lb
Sulfuric Acid	1000 lb	1000 lb

International Regulations

Mexico - Grade Serious risk, Grade 3

Chemical name	Carcinogen Status	Mexico
Hydrogen Peroxide	A3	Mexico: TWA 1 ppm Mexico: TWA 1.5 mg/m³ Mexico: STEL 2 ppm Mexico: STEL 3 mg/m³
Acetic Acid		Mexico: TWA 10 ppm Mexico: TWA 25 mg/m³ Mexico: STEL 15 ppm Mexico: STEL 37 mg/m³
Sulfuric Acid	A2	Mexico: TWA 1 mg/m³

CANADA

This product has been classified in accordance with the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all the information required by the CPR

WHMIS Hazard Class

B3 - Combustible liquid
C - Oxidizing materials
E - Corrosive material
D2B - Toxic materials

16. OTHER INFORMATION

HMIS	Health Hazards 3	Flammability 1	Stability 2	Special precautions h

NFPA/HMIS Ratings Legend
Severe = 4; Serious = 3; Moderate = 2; Slight = 1; Minimal = 0

Protection=H (Safety goggles, gloves, apron, the use of supplied air or SCBA respirator is required in lieu of a vapor cartidge respirator)

Revision date: 2013-02-11
Reason for revision: Initial Release.

Disclaimer
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Prepared By:

PeroxyChem

WATER TREATMENT

End of Safety Data Sheet

Appendix C

Lifecycle Analysis Cost Sheets

PAA Cost Sheet
Peak Contact Time = 31 minutes

Peak Hour Flow	MGD		170
Avg Flow	MGD		90
Influent E. coli - Peak	MPN/100 mL		1,600,000
Target E. coli - Peak	MPN/100 mL		244
Influent E. coli - Average	MPN/100 mL		518,730
Target E. coli	MPN/100 mL		63
LI Peak	--		4
LI Average			4
Contact Time at Peak Flow	min		31
Peak Dose	mg/L		7.7
Peak Residual	mg/L		1.3
Avg Contact Time	min		59
Avg Dose	**mg/L**		7.3
Avg Residual	mg/L		0.4
Tank Size	cf		489,235
Tank Cost	$	$	9,591,263
Present Value PAA Annual Cost	$		142,000,000
PAA Storage and Feed	$	$	4,373,436
Present Value SBS Annual Cost	$	$	-
Total Capital Cost	$	$	13,964,699
Total Annual Cost	$		142,000,000
Lifecycle Costs		$	155,964,699

Annual Costs for Peracetic Acid				
Average treated flow, mgd	90			
Days per year of treatment	365			
PAA dose, mg/L	7.3			
Percent solution PAA, %	15			
Specific density of PAA, lbs/gal	9.7			
Gallons per year, as delivered	1,369,000			
Price per gallon, as delivered	$5.82			$0.60/per lb PAA
Annual chemical costs for PAA			7,968,000.0	
SBS dose, mg/L	-0.9			
Percent solution SBS, %	38			
Specific density of SBS, lbs/gal	11.1			
Gallons per year, as delivered	(56,108)			
Price per gallon, as delivered	$1.55			
Annual chemical costs for SBS		$	(86,968)	
Lifecycle in years	20			
Discount rate	4.13%		*P/A factor =*	
Inflation rate	3.00%		17.87	
Annual Costs for Peracetic Acid		$	7,880,000	
Present Value of Annual Costs		$	141,000,000	

PAA Cost Sheet
Peak Contact Time = 16 minutes

Peak Hour Flow	MGD		170
Avg Flow	MGD		90
Influent E. coli - Peak	MPN/100 mL		1,600,000
Target E. coli - Peak	MPN/100 mL		244
Influent E. coli - Average	MPN/100 mL		518,730
Target E. coli	MPN/100 mL		63
LI Peak	--		4
LI Average			4
Contact Time at Peak Flow	min		16
Peak Dose	mg/L		9.8
Peak Residual	mg/L		3.4
Avg Contact Time	min		30
Avg Dose	**mg/L**		8.4
Avg Residual	mg/L		1.6
Tank Size	cf		252,509
Tank Cost	$	$	5,668,563
Present Value PAA Annual Cost	$		167,000,000
PAA Storage and Feed	$	$	4,373,436
SBS Storage and Feed	$	$	1,441,034
Present Value SBS Annual Cost	$	$	86,625
Total Capital Cost	$	$	10,041,999
Total Annual Cost	$		167,086,625
Lifecycle Costs		$	177,128,625

Annual Costs for Peracetic Acid			
Average treated flow, mgd	90		
Days per year of treatment	365		
PAA dose, mg/L	8.4		
Percent solution PAA, %	15		
Specific density of PAA, lbs/gal	9.7		
Gallons per year, as delivered	1,586,000		
Price per gallon, as delivered	$5.82		$0.60/per lb PAA
Annual chemical costs for PAA		9,231,000.0	
SBS dose, mg/L	0.9		
Percent solution SBS, %	38		
Specific density of SBS, lbs/gal	11.1		
Gallons per year, as delivered	56,322		
Price per gallon, as delivered	$1.55		
Annual chemical costs for SBS		$ 87,300	
Lifecycle in years	20		
Discount rate	4.13%	*P/A factor =*	
Inflation rate	3.00%	17.87	
Annual Costs for Peracetic Acid		$ 9,320,000	
Present Value of Annual Costs		$ 167,000,000	

UV System Cost Sheet
20% UVT

Total Capital Costs	UV Equipment Costs	UV Construction Cost
$ 26,200,000	$ 8,705,000	$ 17,500,000

Annual Costs for Maxson WWTP Facility			
Average treated flow (mgd)	90		
Number of Lamps per MGD @ADF	10.7		
Days per year of treatment	365		
UV dose (mJ/cm2) as T1	19		
Number of lamps at average flow	960		
Power input per lamp (watts)	804		Per Trojan
Annual Electric Usage (kW-hr/yr)	6,710,000		
Electricity cost ($/kW-hr)	$0.076		
Annual electricity costs for UV		$ 510,000	
Guaranteed lamp life (hours)	15,000		From Trojan: Lamp warranty = 15,000 hours
Lamp replacement cost	$450		From Trojan: Lamp price = $450
Guaranteed ballast life (years)	10		From Trojan: Lamp driver warranty = 10 years
Ballast replacement cost	$990		From Trojan: Lamp driver price = $990
Annual costs for lamp replacement		$ 250,000	
Annual costs for ballast replacement		$ 48,000	
Lifecycle in years	20		
Discount rate	4.13%	*P/A factor =*	
Inflation rate	3.00%	17.87	
Annual Costs		$ 810,000	
Present Value of Annual Costs		$ 14,000,000	